THE PRIVATE ECONOMIC BENEFITS OF SOIL CARBON SEQUESTRATION

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ABSTRACT

This research aims to quantify how management decisions in the form of annual crop rotations influence the amount of soil organic carbon (SOC) sequestered and the private benefits of the resulting organic carbon to farmers, using a simulation methodology. Carbon patterns were simulated using a soil turn-over model – RothC – for a representative site in the black soil zone of Saskatchewan. The study then simulated the economic values of the resulting carbon stocks with crop response functions that directly link the nutrients contained in SOC to crop yield. The economic simulation employed three common annual crops, canola, spring wheat, and oats with the fundamental assumption that the value of SOC is inherent in its contribution to crop yield through nutrient mineralization. The carbon simulation utilizes two annual crop rotations to assess soil management impacts on soil organic carbon dynamics over a 20-year duration: a three-year canola-wheat-barley rotation and a four-year canola-spring wheat-canola-barley rotation. The carbon simulation shows marginal but incremental and sustained carbon additions to the soil that average nearly 1.60 t C ha^{-1} yr^{-1} over the entire period. The average annual additions to SOC were proportional (or approximate) to the amounts of the inputs' additions of organic carbon from harvested remains of crops such as residue and stubble. Concurrently, an increase in SOC is accompanied by a reduction in carbon dioxide emissions, suggesting multiple functional roles of soil carbon sequestration, though the study did not include carbon tax in the analsysis. By creating three alternative scenarios, the economic simulations show that the SOC's monetary values range between \$ CAD 0.03 t^{-1} C ha^{-1} and \$ CAD 57.72 t^{-1} C ha^{-1} depending on the crop type and assumptions employed. These boundaries are estimated at 1% and 10% efficiencies of SOC impacts on crop yield and subsequently on farm revenue. With the maximum annual benefits of SOC (i.e. \$ CAD 57.72 t^{-1} C ha^{-1}), an annual sequestration value of \$ CAD 2.00 t^{-1} C ha^{-1} yr^{-1} was obtained. The sequestration value is perhaps less than the annual marginal cost of sequestering carbon found to be \$ CAD 119.00 ha^{-1}. The relatively higher marginal cost compared to the annual benefits suggests providing technical support will boost sequestration activities though this study did not explore if farmers will or should receive them in the future.

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There is no one like family and friends.

DEDICATION

In loving memory of my late father,

Choro Basseh

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LISTS OF ABBREVIATIONS

BIO	Microbial Biomass
BMP	Best Management Practices
CAD	Canadian Dollars
CLC	Conservation Learning Center
DNDC	Denitrification-Decomposition Model
DPM	Decomposable Plant Material
GHG	Greenhouse Gases
HUM	Humified Organic Matter
IOM	Inert Organic Matter
IPM	Integrated Pests Managment
IPPC	Intergovernmental Panel on Climate Change
KgN	Kilogram Nitrogen
KgP	Kilogram phosphorus
MEA	Millennium Ecosystem Assessment
MMT	Million Metric tonnes
PAWC	Plant-Available Water-Holding Capacity
PMB	Private Marginal benefits
PMC	Private Marginal Cost
RPM	Resistant Plant Material
SCPG	Saskatchewan Crop Planning Guide
SOC	Soil Organic Carbon
UK	United Kingdom
USA	United States of America

CHAPTER ONE

INTRODUCTION

1.0 Background

This chapter presents a background to agroecosystem services and their interactions. The discussion provides the backdrop to the problem statement and the objectives of the study. The final section justifies the research that directly leads to the literature review, which assesses previous research on the ecosystem service, soil carbon sequestration, and soil carbon's economic value.

1.1 Ecosystem services and disservices

The interactions between agriculture and the rest of the environment are complex. These interactions generate feedback-effects and produce both positive and negative effects that influence ecosystem services (Tillman et al., 2002; Power, 2010). The Millennium Ecosystem Assessment (MEA) classified ecosystem services into four major categories: provisioning services, supporting services, regulation services, and cultural services (MEA, 2005). The services are supplied by various ecosystem functions that are influenced by natural and human activities, both deliberately and unintentionally (Zhang et al., 2007).

A diverse category of these services provided by agriculture is the regulating services (Swinton et al., 2007). Agricultural management regulates the population dynamics of pollinators, wildlife, and fluctuations in soil loss, water quality and supply, and climate regulation (Swinton et al., 2007). Agricultural production systems influence climate regulation through carbon cycling and greenhouse gas emissions (Johnson et al., 2012). Precisely, agriculture is estimated to contribute nearly twenty-four percent of greenhouse gas emissions worldwide, but it could also contribute significantly to climate change mitigation through increased carbon sequestration and storage (Pachauri et al., 2014). The welfare benefits provided by this soil carbon sequestration are estimated by what all members of society would be willing to pay for it (Mendelsohn and Olmstead, 2009). However, to estimate the economic benefits of such a service to farmers as private decision-makers require indirect economic estimation techniques that are theoretically consistent with market prices or demand and supply functions (Mendelsohn and Olmstead, 2009).

Quantifying the exact economic value of ecosystem services such as carbon sequestration remains problematic in practical applications (Johnson et al., 2012). Johnson et al. (2012) attribute this to the fact that, albeit some ecosystem services support the production of goods with observable market prices such as crops or timber (provisioning service), many ecosystem services have no such explicit signal of value. The lack of observable market prices stems from the flows of these services and disservices that directly depend on how agricultural ecosystems are managed and upon the diversity, composition, and functioning of remaining natural ecosystems in the landscape (Zhang et al., 2007). With many ecosystem values not represented by market prices, there is also ambiguity about carbon sequestration values since valuation techniques often capture only a portion of potential value (Mendelsohn and Olmstead, 2009) or provide theoretical dollar amounts not linked to actual expenditures (Diamond and Hausman, 1994). However, the ability to place values on soil carbon is central to designing policies that encourage agricultural land managers to provide (or maintain) services at levels that are desirable to society (Swinton et al., 2007).

Swinton et al. (2007) propose that research is required to design cost-effective incentives to provide services such as carbon sequestration and to evaluate which incentives could provide the most significant welfare benefits to society. To fully account for both the costs and benefits of alternative agricultural practices, society must recognize the net benefits of agriculture, and that such an accounting must become the foundation of policy, ethics, and action (Tilman et al., 2002). As such, it is imperative to understand better the interactions between agriculture with the environment on the one hand and to adequately measure the associated costs and benefits on the other hand. Besides, there is the need for fundamental shifts in institutions, policies, and incentives in the search for, and broad adoption of sustainable agricultural practices that will enhance carbon sequestration and this search must be an on-going and adaptive process (Tilman et al., 2002).

Since soils are often the primary natural capital base that yields the flow of these valuable ecosystem goods and services into the future (Dominati et al., 2010), any linkage between policy interventions and ecosystem service provisioning would require a better understanding of the soil and its production parameters. Such nexus exists in the form of soil organic carbon (SOC) that provides crucial benefits to both land users and the environment.

Therefore, this research empirically links soil quality parameters with ecosystem services and land productivity in terms of agricultural commodities through SOC. Soil scientists regard SOC as the most important indicator of soil quality and agronomic sustainability because of its impact on other physical, chemical, and biological indicators of soil quality (Reeves, 1997). It serves as a primary gauge of both soil quality and health for scientists and farmers (Roming et al., 1995), and the provision of carbon is a significant source of energy for soil microbes. The decomposition and subsequent mineralization of SOC release major soil nutrients (including nitrogen (N), phosphorus (P), and potassium (K)) for plant growth. These complex and multiple functions also influence soil structure, which in turn impacts crop productivity (Reeves, 1997). Besides, SOC has been adjudged the best indicator of soil quality for its influence on other soil properties such as pH, electrical conductivity, and cation exchange capacity (Reeves, 1997). Therefore, measuring the private monetary benefits of SOC concerning crop productivity is paramount in shaping landscape management decisions in terms of conservation usage.

1.2 Justification of the research

Farmers are the ultimate decision-makers regarding land use and management practices. However, scientists can contribute to sustainable land management by translating scientific knowledge and information on soil functions into practical tools and approaches by which land managers can assess them (Doran and Zeiss, 2000). Before any policy that aims to increase carbon sequestration and the resulting carbon stocks yield its potential benefits, the policy must induce farmers monetarily as the primary incentive to adopt such practices . In many cases, farmers are the primary beneficiaries of the sequestered carbon generated therein (Power, 2010). Therefore, it is crucial to redefine the different benefits associated with land use that would be useful to farmers and guide policymakers in analyzing different tradeoffs in land use policy.

The analysis of the services provided by SOC and the need to include it in decision-making to achieve sustainable development began around the late 1960s (Awada et al., 2016; Dominati et al., 2010). This recognition is growing rapidly and globally (Daily et al., 2009). The cumulative losses in SOC (United Nations, 2011) persuade society to reconsider how to integrate the value of these services into farm-level decision-making (De Root et al., 2010). Thus, as most soils produce several services, their benefits need to be evaluated. This analysis's success typically rests on two pillars: the scientific community's need to deliver the knowledge and tools to forecast and quantify these returns and the ability to integrate this knowledge into the decision-making process (Daily et al., 2009). This research contributes to both pillars by first translating our existing knowledge on natural capital (or SOC) into ecosystem services (i.e., carbon sequestration) and then integrating those outcomes into land-use decision making. This integration is so fundamental to the ability to manage soils to enable them to deliver their diverse/multiple functions. By valuing soil carbon, it would provide useful information to institutions that guide resource management and land use policy (Daily et al., 2009). As much as carbon sequestration is a plausible mechanism for reducing atmospheric carbon dioxide concentration with the least cost, the economic benefits to farmers as private decision-makers need to be understood

1.3 Motivation

The soil, climate, and land management practices all impact SOC. Among these factors present in the agricultural production system, it is the management component that farmers can control. Contemporary research has evaluated the ability of soils to store an additional amount of carbon (Lewandrowski et al., 2004). This carbon storage potential of the soil provides benefits to society in several extents. First, soil carbon storage enhances the soil to nourish plants with nutrients such as N, P, sulfur, and water storage improvements (Khakbazan et al., 2011). Also, increasing SOC means that agriculture could become a net carbon sink rather than an emitter of global carbon dioxide. These interrelated benefits of carbon sequestration can be augmented through changes in land use and by adopting suitable production practices possible (Antle et al., 2001).

Several researchers (e.g., Janzen, 2006; Chiti et al., 2010) have highlighted that increasing the soil carbon levels increases the yield of most crops by augmenting crop nutrients. However, it is not well quantified what the net gain in revenue farmers could expect due to adopting management practices that build up these carbon stocks. Therefore, this research aims to quantify those benefits associated with management practices that impact SOC and the resulting farm revenue.

1.4 Problem statement

Carbon sequestration is an alternative, cost-efficient means of cutting atmospheric carbon dioxide (Antle et al., 2001; Lewandrowski et al., 2004; Meyer-Aurich et al., 2006), therefore an essential agroecosystem service. The rate of this carbon sequestration can be altered with the adoption of alternative agricultural management systems. Such management strategies as the adoption of conservation tillage, management of crop residue, including perennial crops in crop rotations, choices of different crop varieties, and conversion of annual cropland to perennial forage and forestry have already been documented (see Powell, 2001; Baker et al., 2007; West and Post, 2002 and the references therein).

However, how these services contribute to the value of agricultural outputs have had limited empirical attention. One ecosystem service that is an essential component of productive agricultural systems is the function of sequestering carbon in the soil and the resulting stocks of soil carbon. Carbon stocks in the soil positively impact crop yields and mitigate carbon dioxide emissions resulting from changes in land use (Lewandrowski et al., 2004; Meyer-Aurich et al., 2006). These concerns raise the need to estimate a monetary value on carbon stocks that yield benefits to farmers as private decision-makers.

This study extends this economic evaluation to include an assessment of the economic benefits associated with soil management practices that impact soil carbon stocks and the value of these soil stocks to agricultural producers.

1.5 Objectives of the study

This research aims to estimate the economic benefits of management choices that impact SOC and the provision of productive ecosystem services that yield private benefits to farmers. Precisely, the study addresses the following specific objectives:

1. Represent the relationships between management practices and changes in soil carbon stocks.

This objective will link different soil management practices (i.e., alternating crop rotations) to soil organic carbon (i.e., carbon sequestration) and ecosystem services generated that contribute to crop productivity.

2. Quantify the economic (monetary) benefits of carbon sinks (or stocks) generated from the soil.

This objective will translate the carbon stocks into the net revenue of agricultural productions by linking it to crop productivity and crop yield.

3. Evaluate the relative benefits and costs of alternative management systems in soil productivity in annual crop production.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

Chapter two discusses four dimensions of soil carbon sequestration. The first section reviews the role of the soil in sequestering carbon. The second section then discusses how soil management, in terms of reduced-tillage and enhanced crop rotations, could influence the resulting soil carbon stocks. This discussion provides a pathway to understand how useful, such carbon can be to crop farmers. Next, the third section assesses different estimations methods in the literature that provide different ranges of estimates on the monetary value of SOC. Section four then discusses the development of policy instruments and how subsidies and incentives could be used to drive farmers to adopt management practices that result in higher rates of soil carbon sequestration and more extensive soil carbon sinks.

2.1 The flow of carbon in the soil and atmosphere

The equilibrium of carbon on earth is a function of three reservoirs: the oceans, atmosphere, and terrestrial systems (Eswaran et al., 1993). With each of these reservoirs holding a different quantity of carbon across time, it is on the terrestrial systems that the stored carbon proves to be useful. The soil is the center of the terrestrial system, on which most agricultural activities occur (VandenBygaart et al., 2003). Estimates consistently indicate that undisturbed soils have enormous storage potential for soil carbon relative to the corresponding cultivated soils (see VandenBygaart et al., 2003; Powell, 2001). The rise in agricultural activities means the equilibrium levels of the stored carbon must be stabilized (Lewandrowski et al., 2004).

Carbon sequestration is the process of capture and long-term storage of atmospheric carbon dioxide (CO_2) such that the concentration of atmospheric carbon dioxide reduces (Sedjo and Sohngen, 2012). Natural (photosynthesis) or anthropogenic processes can accelerate this removal. With carbon being the primary constituent of most plants and animal material, SOC is stored in organic matter in the soil, which serves as the nutrient and energy source for biota (Janzen, 2006). However, before the organic matter becomes useful to agricultural production, it must decompose. It is this decomposition process that releases carbon into the atmosphere as carbon dioxide. In the atmosphere, carbon dioxide becomes a stable form of carbon.

Moreover, carbon dioxide can be recycled back into the soil through carbon sequestration, which would serve a useful purpose. The foregone arguments of SOC decomposition to release carbon dioxide and its recycling back into the soil prompt two inevitable inferences. First, delaying the decomposition of organic carbon can reduce the release of carbon dioxide (Janzen, 2006). Second, soil carbon stocks can be increased by sequestering carbon dioxide from the atmosphere. However, these two processes are paradoxical as we need organic matter to decay to release nutrients, and the decomposition process releases carbon dioxide (Lal and Kimble, 1997). Janzen (2006), therefore, suggests the balance of soil carbon inflows (carbon sequestration) and outflows (decomposition) be enhanced by intensifying carbon sink. Besides, limiting the decomposition process to timely requirements of soil carbon can also prove fruitful. Minimizing organic matter decomposition during fallow periods and enhancing its decay during the planting period can optimize the flow of carbon in the soil and the atmosphere (Janzen, 2006).

2.2 Soil management and soil carbon sequestration

Studies on carbon sequestration and the resulting global carbon stocks are both historical and recent, highlighting the research's usefulness in that direction (Antle et al., 2001). However, the majority of these studies are focused on the 'technical potential' of carbon sequestration. Actual results show that soils can sequester more carbon from the atmosphere, thereby acting as an essential way to mitigate climate change. This knowledge is crucial since increasing demand for food requires large land areas to be cleared for these agricultural activities. Thus, adopting management practices that either reduce soil carbon emissions or increase carbon sinks is paramount in the realization of such a global vision.

Typical of agricultural production, improving crop productivity in part depends on the soil and crop management practices that increase SOC (Havlin et al., 1990). Conservation tillage, a generic term for tillage practices that decrease the frequency and intensity of tillage, including minimum tillage and zero tillage, that reduce soil and water losses compared to conventional tillage (plow-based), has been frequently called for in the literature (see Lal and Kimble, 1997). Plus, conservation tillage is often adopted with appropriate annual crop rotations. These management practices can potentially increase the stocks of SOC (West and Post, 2002). Kimble et al. (1998) gave insight by estimating that conservation tillage and residue management can achieve 49% of carbon sequestration, while 25% of sequestration is achieved by changing cropping practices. Augmenting practices such as land restoration efforts (13%), land-use change (7%), and better water management (6%) could fully explore the potential of agricultural carbon sequestration (Kimble et al., 1998).

The literature has further diverse findings in support of the assertion that zero tillage and crop rotation have a substantial influence on building soil organic carbon. For instance, West and Post (2002) experimented with decreasing tillage intensity and alternating crop rotations potential to sequester SOC. They found that enhancing rotation complexity can sequester, on average, 20 ± 12 g C m^{-2} yr^{-1}. Whereas changing from conventional to zero tillage can sequester 57 ± 14 g C m^{-2} yr^{-1}. With soils that have degraded SOC levels, West and Post (2002) noted that enhanced rotations and zero tillage both have the potential to restore soil carbon equilibrium in 40 to 60 years, and 15 to 20 years, respectively.

Blanco-Canqui and Lal (2008) reported from the eastern United States that zero tillage has a significant influence on the influx of SOC and organic N than conventional tillage, especially on the top profile of the soil horizon. Their study focus on the SOC distribution along with the soil profile and a long-term basis. It was only below the 10 cm horizon that Blanco-Canqui and Lal (2003) found that zero tillage did not show any appreciable effects on soil carbon than conventional tillage. Among Kansas soils, Havlin et al. (1990) found zero-tillage to impact soil carbon relative to conventional tillage significantly. They concluded that crop management systems that combine rotations with high residue-producing crops with reduced-tillage result in the greater SOC levels.

The relevant literature points to the inference that enhanced crop rotations and reduced tillage provide a pathway to restoring soil organic carbon towards the level of carbon storage found in undisturbed soils. Differences in scope, methodologies, geography, and assumptions make it difficult to thoroughly compare past studies on carbon sequestration levels (Lewandrowski et al., 2004). However, these studies provide an excellent preamble towards addressing concerns over technical potential, using subsidies to enhance sequestration activities and evaluating the monetary values of soil carbon stocks.

2.3 The economics of carbon sequestration

2.3.1 Economic incentives and carbon sequestration

With the rising concerns of carbon sequestration, much of the economics literature focuses on addressing how incentives such as subsidies could induce farmers to adopt management practices that sequester carbon (See Lewandrowski et al., 2004 and the literature therein). This section provides an overview of studies that attempt to address the knowledge gaps identified in the economics literature vis-à-vis economic incentives and soil carbon sequestration.

A crucial foundation study in this area is Lewandrowski et al. (2004), who examine two distinct components of carbon sequestration.Their study determine how much of the estimated technical potential for additional carbon sequestration is economically feasible. Second, they examine the cost structure of alternative incentives that can induce carbon sequestration. Using the US Agricultural Sector Model, Lewandrowski et al. (2004) confirm that agriculture offers low-cost opportunities to store additional carbon in the soils, though higher costs than anticipated. Their finding aligns with other studies such as Plantinga et al. (1999), who note that previous studies underestimated the costs of sequestering carbon. In their approach, they factor in farmers' adoption decisions, the tradeoff between the additional costs of sequestering practices relative to the additional returns from per tonne carbon payments. They also simulate farm scenarios where governments pay farmers subsidies to convert their croplands to forestry. By simulating subsidies levels up to \$125 ha^{-1} for farmers to adopt sequestration activities, only 7 to 27 MMT of additional carbon would be sequestered annually on a national scale, representing one-fourth of the technical potential projected in soil science studies.

Lewandrowski et al. (2004) conclude that payments that induce emissions reduction are superior to those that pay farmers to sequester carbon. They reach this conclusion based on the realization that to store sequestered carbon in the soil permanently, the payment structure would have to be indefinite. If governments abrogate the payments contracts and farmers return to their conventional practices, the stored carbon would eventually be released into the atmosphere rendering the initial purpose of the program naught (Lewandrowski et al., 2004).

Nonetheless, a broad area of consideration might involve subsidizing farm technology that would foster soil carbon sequestration. In that case, governments can make, for example, an indirect intervention by promoting investments in research and development (Awada et al., 2016). This intervention may provide producers information to enable them to make decisions to orient their management practices in favor of those that sequester carbon. Awada et al. (2016) demonstrated the benefits of zero-tillage technology investment in the Canadian prairies. Using the costs-benefits framework, these authors found a return of \$ CAD109.30 ha^{-1} to the agricultural sector on every \$1.00 invested in research by the public sector in zero tillage development and research spanning over 27 years (1985-2012). However, subsidizing farm technology requires that we outline the specific farming strategies that would maximize carbon sequestration and indicate how much investment would optimize the government expenditure in that regard.

Other researchers examined whether the private benefits of adopting those practices will induce farmers to foster carbon sequestration compared to research approaches that focus on policy incentives and payments to encourage the adoption of carbon sequestration management. This ideology is consistent with observations to make the sequestration process permanent (see Lewandrowski et al., 2004). The argument is that, notwithstanding our superficial understanding of how incentives structures would make farmers adopt practices to sequester carbon, only a few countries have those incentives in place at first and to implement them at large. Finally, another related area of research focuses on the internal incentives relating to the conversion of marginal agricultural lands to forestry (Parks and Hardie, 1995). This conversion, if adequately adopted, should not only sequester carbon but also restore low-productive lands for future cultivation (Lal, 2003). Besides, a substantial fraction of the carbon will retain in wood products for long periods after harvest (McCarl et al., 2005). As highlighted by

Lewandrowski et al. (2004), if indeed carbon sequestration in soils remains a cost-effective approach for global carbon mitigation, it needs to be reinforced while searching for technologies that would separate, capture and store carbon dioxide from the atmosphere efficiently.

2.3.2 The value of soil carbon

Soil carbon has monetary value that links it to economic assets that provide benefits for humans (Pascual et al., 2015). These economic assets include improving crop yields, augmenting soil erosion control, enhancing soil quality, and providing nutrients source to soil biota. Quantifying this economic value can provide information about the priority of investment in soil carbon relative to other investments (Pascual et al., 2015). For policy analysis, the full range of costs and benefits associated with carbon sequestration must be understood. Specifically, this study highlights the benefits of soil carbon directly related to crop productivity and provides returns to farmers as private decision-makers.

To the farmer, increasing SOC stocks are seen as a means to cut down on the use of inorganic fertilizers, but they still meet the crop nutrient requirements (Petersen and Hoyle, 2016). Soil organic carbon can play a significant role in land productivity and crop yield (Pascual et al., 2015) through increased plant-available water-holding capacity (PAWC) (Petersen and Hoyle, 2016). Where N availability limits crop production, increasing SOC can increase potential yield relative to other constraints by increasing the biological supply of nutrients from organic matter turnover (Petersen and Hoyle, 2016). Other related benefits of management options that increase soil carbon include the reduction in tillage intensity, which can also mitigate soil erosion. However, Pascual et al. (2015) highlighted that reduced tillage intensity might also result in increased use of pesticides to control weeds with pesticide runoff to water bodies negatively impacting water quality and aquatic organisms.

Some research has focused on quantifying the monetary value of soil organic carbon in an agricultural context (Table 2.1). These estimations have tended to emphasize the on-site benefits to farmers, as the off-site benefits are intertwined and difficult to quantify. For instance, Petersen and Hoyle (2016) determine the marginal value of SOC in Western Australia to lie between AU\$7.10 and AU\$ 8.70 t^{-1} C ha^{-1} yr^{-1} depending on crop type and rainfall zone. Among other factors, they estimate that AU$ 6.60 t^{-1} C (75%) of the resulting carbon value emanate from sequestration. Also, they attribute 20% of the resulting value to N-replacement, and 5% to estimated productivity improvement. Spanning 50 years, Petersen and Hoyle (2016) noted their values are sensitive to variation in both fertilizer and carbon prices though that did not change the conclusions of their estimates substantially.

Table 2.1 Estimated benefits of SOC

$ values of t^{-1} C (ha^{-1} yr^{-1})	Period (years)	Present $ value over the period (t^{-1} C ha^{-1} yr^{-1})	Country	Reference
AU$7.10-8.70	50	$130-160	Australia	Petersen and Hoyle, 2016
$0.20-$2.10	50	$9-$234	Canada	Belcher et al., 2003
US$3.15	20	$231.53	USA	Wander and Nissen, 2004

In a related study, Belcher et al. (2003) use a dynamic simulation model to quantify the impacts of different crop rotations on soil organic carbon among Canadian prairies. They estimate such value of on-site SOC changes to range from $ CAD 0.20 t^{-1} C ha^{-1} yr^{-1} to $ CAD 2.10 t^{-1} C ha^{-1} yr^{-1}. Similarly, Belcher et al. (2003) noted that over 50 years, the present value of carbon could be as high as $CAD 234.00 t^{-1} C ha^{-1} yr^{-1}.

For US agricultural soils, Wander and Nissen (2004) report a marginal value of SOC to be US$ 3.15 t^{-1} C ha^{-1} yr^{-1}. They further decompose this marginal value into a productivity enhancement value of US$ 2.73 t^{-1} C ha^{-1} yr^{-1}, the fertilizer replacement value of US$ 0.40 t^{-1} C ha^{-1} yr^{-1}, and water quality enhancement of US$ 0.02 t^{-1} C ha^{-1} yr^{-1}. Unlike the previous two estimations, Wander and Nissen (2004) compound carbon sequestration of 0.35 t C ha^{-1} at $20 t^{-1} over 20 years and note the present value of the SOC to be $140.00 ha^{-1}. Nevertheless, as indicated by Pascual et al. (2014), in valuing SOC, it is paramount to account for the impacts on mean yield and the impact on the variability of yield in response to environmental and climate variability. Thus, in a more recent study by

Oldfield et al. (2019), they estimate the value of SOC by linking it to the potential yield impact SOC would have if soil carbon reaches its equilibrium quantity in the soil. They project this potential equilibrium value at 2% (of the soil) and predict an additional gain in yield for maize and wheat would reach as high as 5% and 10% of the global annual tonnes produced, respectively. Although this estimation did not give a precise monetary value to SOC, it linked SOC to crop production with an economic value through crop prices.

2.4 Summary and conclusion

This section of the study recaptures the various contemporary issues about agricultural carbon sequestration—such concerns as those relating to management practices that impact agricultural carbon stocks. The section identifies policy advocacies such as the call for the introduction of incentives to encourage farmers to adopt management practices with significant influences on soil carbon stocks. The chapter then concludes by assessing the benefits farmers would gain if the government fails to introduce such incentives in the first place. Accordingly, the chapter reviews previous studies that tend to estimate the economic value of soil carbon to farmers as private decision-makers.

Soil carbon sequestration, which gains recognition following the revolution in crop production practices such as the adoption of crop rotations and zero-tillage, needs more research focus. The literature all paint a good picture of soil carbon in terms of the essential roles it plays in shaping agricultural production systems, and as such, monetizing SOC has become an indispensable focus of current research. Moreover, because land management practices that build up soil carbon are capital intensive, the literature advocates for the introduction of incentives to encourage adoption in agricultural landscapes. The arguments in favor of introducing incentives to encourage the zero-tillage adoption stem from the uniquely public nature of soil carbon sequestration. The reduction of carbon dioxide levels in the atmosphere associated with carbon sequestration, for instance, is a national priority under the Paris Agreement, in which Canada is committed to reducing its GHG emissions by 30% below 2005 levels by 2030.

Finally, in assigning a monetary value to soil carbon, the literature points to the positive economic values associated with increasing soil carbon stocks. However, the estimates differ depending on the methodology, the assumptions underlining the estimation, the geographical area under consideration, the crop type, and the study areas' rainfall distribution. Despite the differences in the empirical approaches adopted, the conclusions from these researches did not differ substantially. They all point to the positive outcome associated with building soil carbon reserves.

CHAPTER THREE

CONCEPTUAL FRAMEWORK

3.0 Introduction

This chapter provides a comprehensive overview of the economic theory that serves as the foundation for the research methodology and findings. The first section discusses the theoretical linkages between soil management practices, agricultural production (or output), and soil carbon sequestration. Given this backdrop, the second section develops the conceptual framework that connects them (i.e., soil management, soil carbon, and yield) using structural relations to establish more complete relationships. The supporting economic theory adapts structural equations from previous studies to clarify the relations between management, soil carbon, and crop yield. The chapter concludes by outlining a measure of economic benefits, the marginal value product of production inputs. This marginal value, together with the marginal cost of sequestering carbon, yields the study's economic theory foundation.

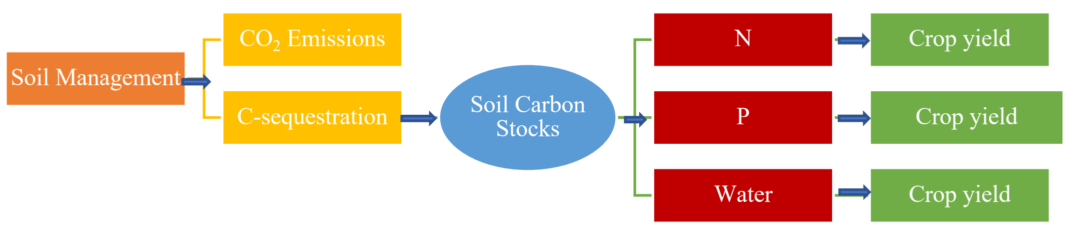
3.1 The conceptual framework

This framework describes how farmers' profit-maximizing behaviors influence management decisions (or choices) and the impact of this management on SOC stocks. The study adopts the approach employed by Antle et al. (2001) in their integrated carbon sequestration assessment in the Northern Plains of the United States. The study then applies the marginal cost concept illustrated in Lewandrowski et al. (2004) to derive the marginal cost of carbon sequestration.

In the decision model developed for this research, farmers first decide their management practices, such as choosing different crop rotations that result in different yield levels and different impacts on the soil structure and content. As shown in Figure 3.1, management practices such as crop rotations (e.g., canola-wheat-barley rotation) or tillage (e.g., conventional tillage versus zero tillage) could influence both the SOC and the amount of carbon dioxide emissions.

Zero tillage is known to conserve SOC, whereas conventional tillage enhances SOC decomposition and increases soil carbon emissions (Baker et al., 2007; Powell, 200; Lal and Kimble, 1997). Thus, depending on the management alternative selected, farmers could end up with more emissions and less sequestration or lower emissions and more sequestration (see Figure 3.1).

Atmospheric carbon dioxide emitted by agricultural activities can recycle back into the soil through sequestration activities. Soil carbon sequestration-enhancing activities range from land management practices such as long-term adoption of zero-tillage technology (Deen and Kataki, 2003), adoption of enhanced rotations to the conversion of marginal agricultural lands into forestry (see Schoeneberger, 2009). Such diversity of activities have been documented in the literature and have proven to impact SOC stocks positively. SOC stocks mineralize to release mineralized N and P into the soil, while more extensive stocks of SOC can also enhance soil water storage capacity. Therefore, with more extensive SOC stocks, and higher mineralization rates, less inorganic fertilizer might be required to supplement crop nutrient requirements (Lal, 2003). Thus, the mineralized carbon and inorganic fertilizers contribute to the needed nutrients to support plant growth and crop yield (see Figure 3.1).



3.1 Impacts of management strategies on soil carbon stocks and crop yields

The dynamics of the soil carbon stocks have been estimated using simulation models in a body of relevant literature. The United Nations Intergovernmental Panel for Climate Change (IPCC, 1997) has developed a theoretical structure to estimate soil carbon stocks in agricultural systems per equation 3.1.

$$\text{soil carbon}_{\text{managed}} = \text{soil C}_{\text{native}} * \text{base} * \text{tillage} * \text{input} \qquad (3.1)$$

Where soil C_{native} is the carbon content in the undisturbed system representing the accumulation of soil carbon under native vegetation, the base parameter represents changes in SOC content due to the conversion of native perennial vegetation to agricultural production. Tillage (e.g., conventional or zero tillage) and input factors (root + stubble) are used to estimate the effect of changes in management practices that occur over the inventory period relative to native conditions (VandenBygaart et al., 2003). Thus, the interaction of the native carbon pool with both tillage and inputs returns to the soil determines the soil carbon levels at any point in time. The size of the soil carbon stocks can influence soil productivity. Through decomposition and subsequent mineralization, SOC releases mineralized N, P and contributes to enhanced soil water (W) storage for plant uptake. Soil fertility is, therefore, a function of the soil carbon stocks, which in turn is a function of the plant nutrients according to the equation (3.2):

$$\text{Soil fertility} \;= \mathrm{f}\,(\text{C\_stocks}\,(\mathrm{N}, \mathrm{P}, \mathrm{W})) \tag{3.2}$$

Where soil fertility is defined as the ability of the soil to release the right amount of nutrients for plant growth, and farmers can choose to influence the availability of plant nutrients (specifically N and P) through management that increases and mobilizes the carbon stocks in the soil. In contrast, the remaining nutrients will then commonly be supplemented by purchased inorganic fertilizer sources. Accordingly, the production function is shown in equation (3.3).

$$\mathrm{Q} \;=\; f\big(\mathrm{l}, \mathrm{k}, \mathrm{lr}, \text{C\_stocks}\,(\mathrm{N}, \mathrm{P}, \mathrm{W})\big) \tag{3.3}$$

Where Q = output of crop, l= quantity of land, k= quantity of capital, and lr=quantity of labor. Following the profit-maximizing approach, farmers have the objective to maximize profit subject to the input prices, as shown in equation (3.4).

$$C = c(w, r, R, s, v) \tag{3.4}$$

Where the r= rental rate of capital, R= rental rate of land, w= wage rate of labor, s is the aggregate unit price of fertilizer that provides N and P, and v represents the unit price of all other variables inputs (such as pesticides, herbicides). The corresponding profit function, therefore, becomes (see equation 3.5):

$$\text{Profit} = \; \mathrm{pf}(\mathrm{l}, \mathrm{k}, \mathrm{lr}, \text{C\_stocks}\,(\mathrm{N}, \mathrm{P}, \mathrm{W}) - (\mathrm{w}, \mathrm{r}, \mathrm{R}, s, \mathrm{v}) \tag{3.5}$$

Where p is the unit price of output, in this case, the price of annual crops. The crop production input variables of interest in the present study are N, P, and W. Specifically, how changes in the available N, P, and W from SOC influence farmers' decisions on the amount of inorganic fertilizer to apply. So, the question is, do farmers have the incentive to adopt SOC enhancing management practices relative to supplementing all plant nutrients through inorganic fertilizers? To address this question, the study first quantifies;

1). How management practices (i.e. tillage and crop selection) influence carbon stocks? and

2). How the soil carbon stock influences the production costs, yields, and profits farmers obtain

The study assumes that farmers will adopt specific management practices if and only if the private marginal benefits (PMB) of the management adoption exceed or equal to the private marginal costs (PMC) of doing so (Antle et al., 2001). The notion here is that farmers were initially using lands for activities that bring the highest levels of economic returns (Antle et al., 2001). Economic theory shows that the optimum decision occurs where the two equalize (i.e., PMC=PMB). Therefore, a measure of the costs associated with changing management decisions is required.

3.1.1 Cost of sequestering carbon

Lewandrowski et al. (2004) highlight that the marginal cost (MC) of sequestering additional units of carbon rises as the quantity sequestered increases. This highlight coincides with the Antle et al. (2001) proposition that estimated the marginal cost of converting agricultural lands to forestry, for example, shows higher marginal costs in the form of rental payments as more quality lands are converted. To sequester additional carbon at the landscape scale requires additional land conversion into land-use alternatives that have higher carbon sequestration rates, management practices (such as adopting zero-tillage) would have to be intensified, and new farming techniques have to be adopted (e.g., cropping system that involves cover crops). The marginal costs capture variable input-decisions and the cost of the foregone opportunities associated with the initial farming activities, such as introducing cover crops into the rotation to increase sequestration. As such, all the marginal costs curves in this modeling slope upward, as indicated in Figure 3.2. An upward-sloping marginal cost curve for the soil in a region reflects the fact that different land units have different opportunity costs (Antle et al., 2001). Nonetheless, the relative slopes of the curves are not necessarily accurate for this study as the research does not aim to quantify which of the two methods is efficient.

The derivation of the marginal cost of sequestration in this section draws the foundation from Lewandrowski et al. (2004), who used a similar intuition to develop the MC for sequestering carbon in the U.S. using zero-tillage and crop rotations as the basis of their model. This study assumes three scenarios that farmers adopt to achieve sequestration to derive the marginal costs of sequestering carbon. I attain this derivation by adopting alternative crop rotations or changing tillage management, or both. The marginal cost curves of the corresponding scenarios represented in Figure 3.2 are, therefore, hypothetical and do not represent the actual relationships found on agricultural land, with the following marginal cost functions represented, MC_R, (crop rotations), MC_Z (tillage management), and MC_{RZ} (crop rotations plus tillage management). The rising marginal cost curves reflect that under any actual price for sequestered carbon (e.g., offset payment for carbon sink services) there would result some additional use of zero-tillage or rotations (Lewandrowski et al., 2004).

Figure 3.2 further highlights two crucial observations. First, at lower levels of sequestration (similar in Lewandowski et al. (2004)), (X_R), the cost associated with rotations (MC_R) is lower than adopting the zero-tillage (MC_Z) technology. Thus, the vertical line from X_R crosses the MC_R-curve at a lower point. This initial higher cost associated with tillage could account for the cost of new machinery required in the new tillage system. However, as the levels of sequestration increase, to say X*, the machinery's investment would have been made, and the average cost declines substantially as the costs are distributed across a larger area of land. The combined effects of alternating rotations and changing tillage, MC_{RZ}(dotted line) lies primarily below the original management marginal cost curves. This imaginary line shows that merging the two management practices has the potential to decrease the cost of sequestration compared to any of them. Besides, the two practices could function in synergy to potentially foster higher levels of sequestration at the least cost (Havlin et al., 1990). Similar to the highlights in Lewandrowski et al. (2004), using the two management (MCRZ) would allow low-cost producers to adopt both crop rotations and tillage to sequester the required carbon units. That is, to sequester X* units of carbon, for instance, rotations would be used to sequester X_Z while zero tillage would be used to sequester the remaining ($X^* – X_Z$) carbon.

Second, all the MC curves starting above zero signify the non-zero cost associated with any sequestration level. The non-zero marginal cost notion arises from the fact that, sequestration is achieved at a cost, as farmers would need to adopt alternative practices to enable carbon sequestration and these adoption practices come with a price.

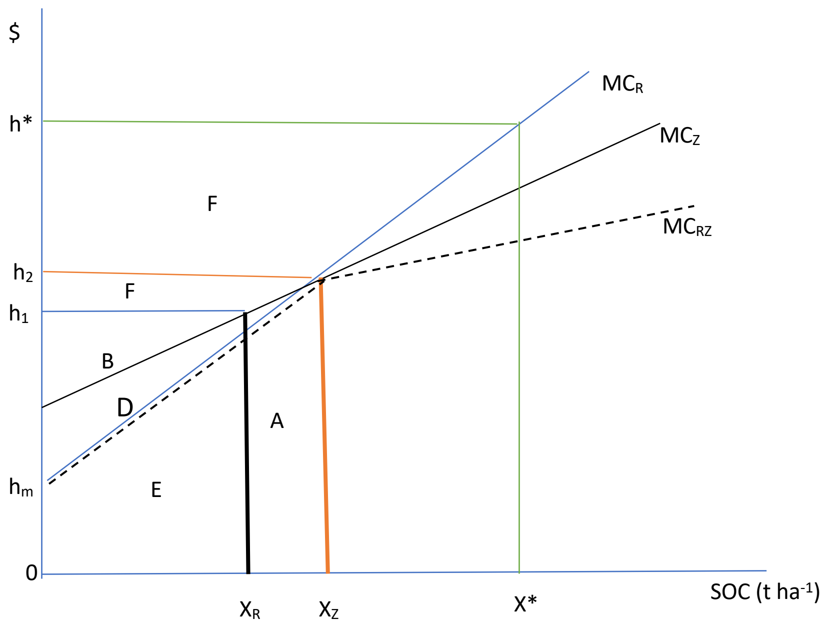


Figure 3.2 The marginal cost of sequestering carbon

(Source: The Economic Research Service, USDA)

Given this backdrop, this model hypothetically represents the marginal cost of sequestration and the conventional measure of producer surplus using mathematical relations. For instance, the total variable cost of increasing sequestration from X_R to X_Z by adopting zero-tillage is the area under MC_Z-curve bounded by the thick vertical lines, designated here as A. This area is represented mathematically as:

$$A = \int_{h1}^{h2} \text{MCz}(X)\,dX \tag{3.6}$$

Where X is the quantity of carbon sequestered in the soil as SOC, and h1 and h2 are the limits of integration that represents the offset payments for carbon sinks. Intuitively, this area represents how much additional cost would be incurred by increasing sequestration levels from X_R to X_Z by adopting zero-tillage technology. The same intuition can derive any cost with a given level of carbon and the corresponding MC curve. Given the MC of sequestering carbon, the entire cost of adopting the management practice can be obtained by adding the fixed transaction costs (such as the cost of land or machinery) (Antle et al., 2001) accordingly (see equation 3.7)

$$\text{Total costs}(X), \text{TC} = \int_0^{h*} \text{MC}(\text{X})\text{dX} + \text{fixed costs} \tag{3.7}$$

In this research, the marginal cost of sequestration is estimated with a proxy value from the cost function depicted in equation (3.4). This value is equivalent to the average price of N and P represented in the cost function as ***s***, which is the cost of inorganic fertilizer saved by sequestering an additional one-tonne value of organic carbon. The marginal cost values are further discussed under the results chapter.

3.1.2 Benefits of sequestering carbon

The PMB of increasing carbon stocks in the soil can be measured by changes in crop yields associated with any change in the availability of mineralized N, P, and water availability for plant uptake. Therefore, if the larger stocks of SOC affects yield by a coefficient, **φ**, interpreted here as the marginal productivity of carbon, then equation (3.3) becomes:

$$\frac{\partial Q}{\partial \text{C\_stocks}} = \varphi > 0 \tag{3.8}$$

Given the unit price of the output is p, then the value marginal product (VMP) of carbon is $p\frac{\partial f}{\partial \text{C\_stocks}}$. At the social optimum levels,

$$p\frac{\partial f}{\partial \text{C\_stocks}} + \beta = \text{s} \tag{3.9}$$

Where β is a marginal public benefit to sequestering carbon. The study further assumes farmers do not consider the public marginal benefits of sequestration in their decisions because no law regulates the amount of carbon farmers should sequester. As such, the restriction β =0, is imposed making the private marginal cost of sequestering carbon, *s* equal to the private marginal benefits, $p\frac{\partial f}{\partial \text{C\_stocks}}$ of the additional carbon stocks.

3.2 Summary of the conceptual and theoretical framework

This framework provides the background information on the existing linkages among soil management choices, soil organic carbon stocks, and crop productivity that serves as a forerunner to the methodology discussed in chapter four. By outlining the theory behind the estimation, this section establishes the foundation of the linkage between management strategies and soil organic carbon stocks. Figure 3.1 highlights the nexus where the structural relationships are discussed.

The benefits of the resulting carbons stocks as underscored are those that relate mineralized N, P, and water to crop yield. For instance, Equation 3.3 establishes that crop yield is dependent on soil nutrients, of which N and P from SOC are an essential source. Equation 3.5, therefore, underlines how changes in the available N, P, and water could potentially influence farmers' decisions through the profit function. Finally, Equation 3.8 provides the value of SOC linked to crop yield. That is, the marginal revenue product relationships developed here form the foundation for measuring the monetary value of SOC in terms of yields. Second, the cost of production that constitutes an essential deciding factor in management choices is discussed with the marginal cost concept. The marginal cost rather than total cost is chosen as the focal point of the discussion to emphasize that farmers make farm-level decisions at the margin. By comparing the marginal cost of sequestration to the marginal value of the resulting carbon stocks, the relative tradeoffs of management decisions are also implied in Equation 3.9.

CHAPTER FOUR

METHODOLOGY

4.0 Introduction

This chapter provides an extension of the conceptual framework by outlining the specific methods employed in the analysis. The first section describes the study area. The subsequent sections highlight two distinct simulations: impacts of soil management (in terms of crop rotation) on SOC using RothC and the monetary values of such SOC using crop response functions (otherwise known as sufficiency curves). The two (both carbon and economic) simulations employ alternative scenarios (two scenarios for the carbon simulation and three for the economic simulation) to simulate a wide range of farm-level decisions made on the agricultural landscape.

The estimations here focus on the on-site benefits of SOC changes, which can be quantified and provide a measure of private benefits to farmers. Following Petersen and Hoyle (2016), I attribute the marginal value of soil carbon in this analysis to two primary sources. First, the increase in the mineralized nutrients (N and P) arising from SOC mineralization. Moreover, second, the improvement in crop yield resulting from an enhancement of soil water retention (specifically, plant-available water-holding capacity (PAWC)). Therefore, the value of N, P, and W sums up the value of SOC to farmers as private decision-makers.

4.1 Study area

The study area is the Saskatchewan Conservation Learning Center (CLC). The CLC is a research and demonstration farm located on 457 acres of land, 18 km south of Prince Albert (AgriARM Report, 2011). The area falls in the black soil zone under the Saskatchewan soil classification. The CLC is distinctive as a research and demonstration facility in that it contains rolling topography, wetlands, and remnant native upland areas (AgriARM Report, 2011). Agricultural activities at the CLC are geared towards the soil, water, and wildlife habitat conservation (AgriARM Report, 2011).

There is widespread adoption of zero tillage and enhanced crop rotations, making it suitable for evaluating the economic benefits associated with such management choices (Samarawickrema and Belcher, 2005). Besides, it is characterized by annual crop production such as cereals (wheat, corn, oats) leguminous and pulse crops (such as lentils and soybeans, respectively) as well as livestock production (especially cattle).

The area's climate is characterized by an average annual precipitation rate between 4.7–112.4 mm and an average annual temperature of -18.8°C to 17.4 °C (see Table 4.6). Owing to the relatively high natural SOC stocks in the black soils, mineralized N and P, as well as the soil's water storage potential, have the potential to be relatively high. As such, farmers are usually not constrained by moisture availability and hence less compelled to summer fallow (i.e., a water conservation management strategy) (Samarawickrema and Belcher, 2005, Belcher et al., 2003). Again, enhanced crop rotations coupled with fertile soils leave abundant crop residues after harvest, thereby further improving soil water conservation (Samarawickrema and Belcher, 2005).

Finally, average yields of crops tend to be higher in the black soil zones compared to the dark brown and brown soil zones in the province, as projected in the Saskatchewan crop planning guide (2019). Thus, I select the soil zone due to its high soil organic carbon content making it suitable for the study at hand. The black soil zone in which CLC is located covers a large area, relative to the dark brown and the brown soil zones. The relative area of the black soil zone in the province of Saskatchewan is shown in Appendix A

4.2 key concepts used in the research

The critical terminologies used in this research include organic N, total N, and plant-available N. Organic N is defined here as that component of the total N in the soil that originated from organic sources, principally from SOC. On the other hand, plant-available N (or mineralized N) is used to denote the proportion of the organic N available for plant usage after mineralization. The literature documents that most of the organic N in the soil is in forms that cannot easily be used by the crop plants. However, after mineralization (conversion of organic N into mineralized forms – also referred to as inorganic N – such as ammonium and nitrate), such N becomes available to the plants for uptake. The values of the mineralized N and P are discussed under the results section to serve as the proxy for SOC's economic values. Total N represents the combined organic and inorganic N that the crop plants utilized for growth.

4.3 Justification for simulation and crop choices

In modeling the soil carbon dynamics over a landscape, Antle et al. (2001) note that it is not practical to measure soil carbon sequestered (or changes) accurately on an annual basis since the process is expensive and time-consuming. Therefore, this research adopts a simulation approach as the alternative to quantify changes in the carbon stocks resulting from soil management over time. Besides, the simulation allows for the introduction of farm-level decisions into the analysis that is not currently prevalent but cannot be ruled out in future agriculture. Also, adopting a simulation approach as the basis for estimating SOC's monetary value using crop response functions appear compelling since the analysis directly links each crop yield to the mineralized components of SOC (N, P) and soil water improvement (W). Therefore, this approach allows the analysis to vary the organic N and P content of each organic carbon while providing a direct estimate of its economic value.

In the first simulation where soil management (in terms of crop selection and rotation) is related to changes in SOC stocks, spring wheat, canola, and barley are the chosen crops for the simulation because there was not enough information on oats to allow for its parameterization. Two of these three crops, spring wheat, and canola, are produced on the greatest land area in Saskatchewan soils. The third crop, barley, although not as commonly produced as spring wheat and canola, is included in the rotations to allow for a greater variety of crop options in the simulation. On the other hand, later in the thesis, barley is replaced with oats in the economic simulation (i.e., second simulation) due to sufficient information on the response function for barley.

4.4 Soil organic carbon simulation

The dynamics of SOC stocks are an essential aspect of crop production as management choices can deplete SOC by degrading organic matter substantially, where decomposition becomes higher than the rate of sequestration (Baker et al., 2007). To value SOC, therefore, there is a need to quantify the accumulation pattern in the soil using an appropriate simulation model. Among other carbon simulation models, such as the CENTURY and the Denitrification-Decomposition model (DNDC), that are used to simulate long-term SOC dynamics across a wide range of ecosystems, this study adopts RothC, a soil carbon turnover model for the soil carbon simulation.

The RothC model is relatively simple in terms of input requirements that are easily obtainable (Coleman and Jenkinson, 2014) with a wide range of applications. It has already been used to simulate carbon turnover on a national scale in the UK (see Coleman and Jenkinson, 2014; Falloon et al., 2006) in Japan (see Shirato and Yokozawa, 2005; Yokozawa et al., 2010) and in China (Yang et al., 2003).

To fit this simulation into the rest of the study (study area), the RothC model simulates organic carbon turnover in non-waterlogged topsoil that adjusts for the effects of soil type, temperature, moisture content, and plant cover on the turnover process (Coleman and Jenkinson, 2014). The model also incorporates land management in terms of crop rotation and selection and transforms crop-residue inputs into SOC and carbon dioxide emissions. By concentrating on the SOC stocks over time, various SOC levels are estimated under different crop rotations in the black soil zone.

4.5 Model description

The current version of the RothC model used in this study, RothC 26.3, is a more recent version of the original model developed by Jenkinson and Rayner (1977). The model is designed to run in two modes: "The forward mode where known inputs are used to estimate changes in SOC over time into the future, and the reverse mode where inputs are calculated from known changes in soil organic matter" (Coleman and Jenkinson, 2014). The model splits incoming plant residue into decomposable plant materials (DPM) and resistant plant materials (RPM) (Shirato and Yokozawa, 2005). Each component decomposes to produce microbial biomass (BIO) and humified organic matter (HUM), releasing carbon dioxide in the process (Coleman and Jenkinson, 2014). The rate of decomposition is defined using modifiers for soil moisture, temperature and plant cover (Falloon et al., 2006) and the specific soil clay content of the soil dictates the proportions of carbon allocated to carbon dioxide, or microbial biomass and humified organic matter combined (Coleman and Jenkinson, 2014).

The model comes with parameters for its validation, which were adopted in this simulation. Among these parameters is the DPM: RPM ratio of 1.44, typical of all crop-plant residues. Again, the recommended DPM= 10.0, RPM= 0.3 BIO= 0.66 and HUM= 0.02, were used (Coleman and Jenkinson, 2014). The inert organic matter pool (IOM), which is assumed constant over time, is obtained from the relation provided in Falloon et al. (1998) as shown in equation (4.1).

$$\mathrm{IOM} = 0.49\mathrm{xSOC}\text{^}1.139 \qquad (4.1)$$

Where the inert organic matter pool (4.98), SOC (t^{-1} C ha^{-1} yr^{-1}) is 57.83 Mg C ha^{-1} in the base year of simulation.

4.5.1 Model parameterization

To parameterize the RothC model to represent the conditions of the study area required exogenous inputs, including monthly precipitation, average monthly mean air temperature (see discussion of weather information under data and sources), and monthly open pan evaporation data (Coleman and Jenkinson, 2014). The monthly input of plant residue (t^{-1} C ha^{-1} yr^{-1}) (see Table 4.1) that returns to the soil from crop residues after harvest account for the model's predictability (Coleman and Jenkinson, 2014).

The model was first run in reverse to calculate the monthly plant residue input required to maintain the carbon stocks level in the base year (2017, in this study). As shown in Table 4.1 for previous studies, RothC estimates carbon input values (see modeled values in column 3) that are generally higher than those calculated from yield values (labeled here as roots + stubble). The higher modeled values imply that the SOC levels in the base year for the respective crops could not be maintained or increased if all crop residues were incorporated into the soil after harvest (Caldwell, 1975). This observation could be based on the conditions of high soil carbon stocks from the original natural vegetation or grassland under which the simulations were carried out (Caldwell, 1975). Land management and weather information are also indispensable in parameterizing the RothC model and influencing its output. As such, for this study, land management scenarios were created to replicate the farming activities that take place at the conservation learning center (CLC).

Following both Yokozawa et al. (2010) and Coleman and Jenkinson (2014), the analysis here assumed crops were planted in May and harvested in September, at which time plant residue returns to the soil. This period is mostly consistent with the seeding and planting schedules that are characteristic of the CLC in most recent years. Moreover, the study also assumed zero farmyard manure application to reflect the real practices adopted on the farmlands in the study area.

Table 4.1 Carbon input (roots + stubble) residue for RothC parameterization

Crop	Residue inputs** (Roots + stubble)	Modeled values	Reference
Wheat	2.70	5.06	Yokozawa et al., 2010
Barley	1.60	1.70	Coleman and Jenkinson, 2014
Canola	1.60*	3.70	Coleman and Jenkinson (2014)

**Assumed based on Coleman and Jenkinson's (2014) calculations.*
*** include values for all inputs including yield*

To complete the simulation of soil carbon stocks over time, I created rotations schemes spanning 20 years. The availability of carbon input data in 2017 for the simulation influences the choice of the base year. With each crop supplying residue input in a single year, the simulation process peaks at year 20. The rotational codes for the simulation are shown in Table 4.2. In the first scenario, each crop is grown in successive order on the same plot of land. However, for the second scenario, either wheat or barley is grown after canola, which is considered a high-value crop in the rotation. Though this three-crop rotation may not be a common conventional rotation system farmers practice, it gives the foundation to understanding how complex management systems and decisions could result in a varied outcome on SOC stocks.

Table 4.2 Crop rotation schemes

Scenario	Rotation Codes
First	SCB…
Second	CSCB…

S= Spring wheat, C = canola, B = barley

4.5.2 Interpreting the output of RothC

The RothC output is analyzed for both SOC accumulation patterns as well as the carbon dioxide emission trends resulting from the rotations adopted in the simulation. The SOC patterns depict changes in soil organic carbon from management practices while the analysis of carbon dioxide emissions helps to understand how the (selected) crop rotations influence GHG emissions. Purposely for this study, the emission reductions are interpreted from the standpoint of best management practices to conserve SOC in the prairies. These sequestration benefits will then be translated into an economic understanding with resulting carbon stocks. Such economic analysis is the purpose of the next simulation presented in sections 4.6 through section 4.9.

4.6 Simulating the economic value of organic carbon

To estimate the monetary values of the resulting carbon stocks from soil management practices, the study focus only on those on-site benefits that can easily be quantified and provide benefits to farmers as private decision-makers. To achieve this aim, I relate SOC to crop yield, which generates a commodity (grain or oilseed) traded in the market. In this case, the contributions of SOC to the revenue farmers obtained is the inherent monetary value of the SOC. Thus, crop response functions that provide those relationships are employed in the estimation.

Part of the estimations here involve two-stages. In the first stage, the marginal value of crop nutrients in the form of total N and P, and water are estimated using the response functions. In the second stage, the simulation then decomposed the N and P into organic and inorganic sources. By attributing the mineralized components of the nutrients to the SOC, this approach elucidates how much of each crop yield, and the resulting net revenue emanates from organic-derived nutrients (N and P). First, the C: N ratio of 10:1 (Parton, 1983; Awada et al, 2016) is used to estimate the amount of organic N in the soil, given the total amount of SOC. That is, 10% of any SOC amount in the soil is estimated to be organic N. Then, 3% of the organic N is assumed to decompose annually, under the highest rate of decomposition predicted by the International Plant Nutrition Institute (IPNI) A further 3% of the resulting decomposed organic N then becomes mineralized N for plant uptake. Between 1% and 10% of the mineralized N is then utilized by plants for growth and yield production.

The carbon to N ratio dictates the amount of mineralized N available in SOC according to equation 4.2

$$K_{Ns} = M(\frac{SOC}{10}) \qquad (4.2)$$

Where SOC is the stock of soil organic carbon available in the soil, M is the mineralization rate (kg $ha^{-1}yr^{-1}$) and directly relates to both temperature and soil moisture (Petersen and Hoyle, 2016). The stock of soil carbon is a function of the initial carbon stock, the annual residue addition to the soil, and the rate of decomposition per equation (4.3) (Moulin and Beimuts 1996).

$$SOC \quad = SOC^{t-1} + \left(R^{t-1} - M\right) \qquad (4.3)$$

Where, R^{t-1} is the annual rate of crop residue additions to the soil (kg ha^{-1} yr^{-1}). The amount of crop residue added to the soil is a function of the crop type and yield (Moulin and Beimuts, 1996).

$$R^{t-1}=Yt * V * HI \qquad (4.4)$$

Where V is the proportion of carbon in the residue; HI is the harvest index (kg residue/kg grain) and Y_t residue from harvested yield.

The two-stage simulation utilizes the SOC stock data and specific crop response functions. Crop response functions are statistical relationships representing how crops, precisely crop yield, respond to production inputs such as plant nutrients and water requirements (Khakbazan et al., 2011). These functions are developed to quantify how crops respond to fertilizer application to identify the nutrients level that optimizes yields, and therefore, profitability (Khakbazan et al., 2011). These functions were developed with the assumption that all other nutrients are available at their validation amounts. Therefore, their derivation aggregates other determinant variables into one, thereby making it possible to measure how changes in the variable of interest impact crop yield. This aggregation means the response functions estimate these relationships independently by considering little or no nutrients interaction in the process. Thus, their architecture is similar to production functions; however, it is developed under biophysical statistical assumptions and methodology. Since the response functions are used to determine the validation nutrients requirement level, in this study, I used these relationships to quantify the marginal value of SOC through yield-response. How such functions are derived is discussed in the relevant literature (see Khakbazan et al., 2011; Petersen and Hoyle, 2016, for more discussions) and summarized in the next section of this chapter.

4.7 Deriving the nitrogen response function

This section underlines the theoretical processes leading to the development of the N response functions. For the complete description of how each of the functions is developed, see the corresponding reference in Table 4.3. The N response function connects mineralized N uptake to individual crop yield. The functions are influenced by the nitrate levels in the root zone as well as the organic N available from the mineralization of soil carbon during the growing season (Oberle and Keeney, 1990). When compared to equation 3.8, equation 4.5 provides a specific linkage between soil N and crop yield. Unlike the former, the latter is well-defined and allows for a precise estimation, which provides a generalized relationship.

Furthermore, equation 4.5 is the overall equation for N response functions. Individual crops have equations with specific coefficients. These specific functions for wheat, canola, and oats are presented in Table 4.3 and were used for the quantification. As shown in equation 4.5, crop yield can be modeled as a function of mineralized soil N as defined by Bowden et al. (2002):

$$Q = VQ * \left(2 * \frac{N}{VQ * G} - \left(\frac{N}{VQ * G}\right)^2\right) \tag{4.5}$$

Where Q is actual crop yield (kg $ha^{-1}yr^{-1}$), VQ is potential yield which is the maximum yield possible when not limited by N availability, (kg $ha^{-1}yr^{-1}$), N is nitrogen uptake by the plants (kg $ha^{-1}yr^{-1}$), and G is a constant that depends on the crop type (0.04 for wheat and oats, 0.07 for canola) (Petersen and Hoyle, 2016). The N uptake, N, by the plant is specified by Bowden et al. (2002).

$$\mathrm{N} = VQ * z * \tanh\left(\frac{Navail}{VQ * z}\right) \tag{4.6}$$

Where z is a constant (0.06 for wheat and oats, and 0.07 for canola) (Bowden et al., 2002); the product of VQ and z gives the maximum possible N uptake by the crop; tanh is a hyperbolic tangent; Navail is crop available N (kg N $ha^{-1}yr^{-1}$) (Petersen and Hoyle, 2016).

The mineralized N is derived either from inorganic fertilizer sources purchased and applied by the farmer or through the organic N made available to the plant through SOC mineralization (Petersen and Hoyle, 2016). Accordingly:

$$\mathrm{Navail} = \mathrm{K_{Nf}} * \mathrm{N_f} + (K_{Ns} * N_s) * (1 - M) \tag{4.7}$$

Where K_{Nf} is a coefficient representing the amount of N from N fertilizer source, and N_f is the quantity of N fertilizer applied (kg N ha^{-1} yr^{-1}); K_{Ns} is a coefficient representing the amount of N present in SOC, and N_s is the quantity of organic carbon (kg N $ha^{-1}yr^{-1}$). M is the summer mineralization factor (Petersen and Hoyle, 2016). Mineralization is defined here as the decomposition of soil organic matter through which nutrients such as plant-available N and P are released (White, 2013). The (1-M) factor, therefore, accounts for the available mineralized N for plant uptake. Due to high temperatures and rainfall in the summer, soils tend to lose a proportion of their mineralized

N (primarily nitrate) through leaching. Thus, M accounts for N that is mineralized but subsequently leached (Petersen and Hoyle, 2016).

Given the N response function presented in equation 4.5, the marginal product function can be derived by taking its first derivative. The resulting marginal product function then relates how changes in the mineralized N correlates to the yield of each crop. These relationships are further discussed in the estimation process. The analytical process leading to the derivation of the P and water response functions are consistent with the N response function and will not be discussed in this study (see Petersen and Hoyle (2016) for the derivation of the water response function). However, the specific equations connecting P and water to each crop used for the simulation are presented at the appropriate places to understand the simulation process and results.

4.7.1 The economic values of soil organic carbon (N and P)

As identified earlier, the monetary value of SOC is estimated using the N, P, and water response functions (revised earlier) independently, relating each crop growth requirement provided by the stock of SOC (N, P, and W). I also replace barley with oats owing to the unavailability of the response function for barley. The specified crop (spring wheat, canola, and oats) and such equations (for the estimations) exhibiting the full connections between carbon (N, P, W) and yields are obtained through the literature reviews. The summary of such equations are present in Khakbazan et al., (2011) and shown in Table 4.3 in this research**.**

To use these response functions for estimation, they were first differentiated to generate the marginal response curves. Theoretically, the marginal response curves measure how responsive the yield of each crop is to, say, an additional N unit. Subsequently, three alternative values of N and P are used collectively under three different scenarios and varied assumptions to estimate the corresponding marginal product of SOC associated with each crop. Such scenarios with their assumptions are stressed below.

Table 4.3 Crop response functions

Nutrients	Functional equations (or forms)	Reference
	Spring Wheat	
Water*	$Y=-0.000016W^2 + 0.011149W-0.915733$	Belcher et al., 2003
N	$Y=-0.000657N^2 +0.694N +3.5$	Phillips and Mullins, 2004
P	$Y=-0.00964P^2 +0.92787P-19.72732$	Kastens et al., 2003
	Canola	
Water	$Y=-0.00003W^2 + 0.0192W-0.52000$	Sidlauskas and Bernotas, 2003
N	$Y=-0.0000274N^2 + 0.0121N +0.772$	Smith et al., 2010
P	$Y=0.003695P^2 + 0.227985P-1.366207$	Roswell et al., 2004
	Oats	
Water	$Y=-0.000005W^2 +0.0045915W-0.0501856$	de Rocquigny et al., 2004
N	$Y=-0.000028N^2 +0.007817N +0.38952$	Mohr et al., 2007
P	$Y=-0.00417P^2 +0.2385P + 0.21876$	Mohr et al., 2007

**The equation obtained through economic modeling. N= mineralized nitrogen, P= mineralized phosphorus and W= Water (PAWC).*

In the first estimation (scenario, also called RothC-output), the resulting carbon stocks from the RothC is used for the simulation. In this situation, I assume 3% of the carbon stocks that accumulate in the final year of simulations mineralizes to release plant-available soil N and P. The resulting N and P from the mineralization are then plugged into the response functions to estimate the corresponding yields. Unlike this estimation (scenario 1), in the subsequent two, the value of soil organic carbon is estimated in two stages. First, total N and total P (from both organic and inorganic sources) that are assumed to produce a yield that maximizes profits of each crop are used. In the second stage, the simulation splits the total effect on yield into an organic and inorganic source. Therefore, the organic component is interpreted to represent the contributions of mineralized carbon to crop yield. However, the results of the inorganic carbon are not presented in this research but can be implied.

In the first of the two latter simulations (scenario 2, using validation values), N and P values that maximized profits of each crop (known here as the validation values and as presented in Table 4.4) are plugged into the marginal product functions and used to estimate the total marginal product values for each corresponding crop and nutrient. Validation values are obtained from experimental stations (unlike the field values from the SCPG) that come with the response functions developed and used in these estimations.

In scenario 3 (using field values), I replace the optimum values with field recommended values. From the viewpoint of field operations and agricultural management decisions in Saskatchewan, the field values of N and P are often provided based on the fertilizer recommendation rates from the Saskatchewan crop planning guide (SCPG, 2019). Here, I assume that the recommended fertilizer application rates are needed to meet the existing soil zones' field conditions and maximize farm profits. It should be noted that these projections are average values for the black soil zone with field-scale recommendations based on farmers testing their soils to identify specific soil needs.

Table 4.4 Validation and field values used for estimation

Input	Validation values	Field Values (SCPG)
	Spring Wheat	
Water	350	350
N	105	108
P	33	42
	Canola	
Water	350	350
N	60	110
P	31	60
	Oats	
Water	450	450
N	139	99
P	28	41

N is measured in kg N ha^{-1} (total N), P is measured in kg P ha^{-1} (total P), water is measured in mm ha^{-1}. Values are taken from Khakbazan et al. (2011) and SCPG (2019). Using these values involves two-stage estimation.

To provide insight into the analysis, it should be reiterated that the validation values used for the estimations are experimentally determined, which correspond to the functions developed for the North American Great Plains and used in this study (Khakbazan et al., 2011). As such, the validation values include nutrients from organic and inorganic sources. For instance, following equation 4.7, mineralized N is obtained from both mineralization of SOC and N from inorganic fertilizer sources. Therefore, there is a need to break down this to determine the percentage of the validation values of N supplied from the organic sources. The fraction of the N supplied to crops that emanate from mineralized SOC can represent its economic value in terms of revenue contribution.

Nevertheless, different soils contain different amounts of SOC, and the N and P content in each of the SOC differ. Thus, the literature is first reviewed to obtain the minimum and maximum amount of organic N and P that is feasible in a given soil. The range of values reported in the literature is presented in Table 4.5 to provide context to my findings.

Given the minimum and maximum values for N and P (see Table 4.5), 3% of those SOC are assumed to mineralize each year to yield N and P, which is available to support plant growth. The resulting nutrients released from the mineralization are then expressed as a percentage of the total nutrients (either validation or field values in Table 4.4) required to maximize profits. The minimum and maximum percentages of these calculations are approximately 1% and 10%, respectively. These proportions of mineralized N and P are termed here as the efficiencies of carbon: measuring how much of the validation yield is contributed by SOC. The discussion thus includes these percentages to illustrate the level of efficiency under which the value SOC is being implied.

Table 4.5 Ratios of carbon to organic N and P (mass of carbon/mass of N)

Nutrient	Minimum	Medium	Maximum	Reference
N	30.00	32.50	35.00	Parton et al., 1987
P	46.00	172.00*	648.00	Stevenson and Cole, 1999

*****_The average of the low and high values based on author's calculations_

To capture the soil water effect through SOC warrants a new set of assumptions to be incorporated into the estimations. In the next section, I describe how SOC influences soil water and, hence, considered in the entire simulation process.

4.7.2 The economic values of SOC through soil water

Unlike mineralized N and P that result from mineralization, SOC's contribution to soil water is more subtle. This idea arises from the contrasting effect through which soil carbon affects water availability for plant uptake. For instance, organic carbon improves soil water holding capacity and increases the aeration of the soil at the same time. Therefore, more water is not always better and cannot be solely used as a measure of SOC contribution to crop yield. Only under drier soil conditions would additional water storage in the soil be beneficial (Petersen and Hoyle, 2016). Besides, under rainfed agriculture as in the study area, farmers are constrained to precipitation and cannot influence the amount of water available to crops through irrigation. Thus, modeling water into the same estimations requires further information and assumptions.

As the response functions for both N and P relate them to crop yield, the water response functions illustrate similar relationships, depicting the optimum amount of water needed to maximize crop yield. As such, the validation values of water reported in Table 4.4 represent the amount of water required to produce yields that maximize the corresponding crops' profits. These validation values of water will, therefore, underpin how SOC's role in water enhancement is modeled in this study. The difference between the validation values of water (in Table 4.4) and the mean annual precipitation (annual mean rainfall of 29.13 mm is calculated in Table 4.6 from the CLC weather information) is assumed to be filled in by the water enhancement-role played by SOC. Such a difference is used to estimate SOC's effect in enhancing soil water storage in improving crop productivity, along with the RothC-scenario discussed earlier. That is, the differences between the two values are plugged into the response functions to estimate the economic value of soil water.

With climate change models predicting fluctuating levels of rainfall (Kang et al., 2009), it is crucial to analyze the crops' responses to decreasing and increasing precipitation levels. Thus, in the next two scenarios, the mean annual rainfall is assumed to increase or decline by 10%, respectively, over the entire simulation period. Thus, the SOC's water enhancement values are adjusted with a 10% increase or decrease in rainfall patterns, respectively, to reflect the fluctuating levels of precipitation in the future. The ensuing gaps between the validation values and the rainfall levels are used in the second and third scenarios, respectively. The resulting yields (using the marginal curves described earlier) from the three estimations are converted into monetary values using the average prices reported in the SCPG (2019).

4.8 Data and its sources

Parts of the data for carbon simulation were provided by researchers that were part of the NSERC Strategic research group, of which this project was a component. The data comprises spatial soils data on carbon, soil depth, pH, and other soil nutrients and plant growth input variables such as N, P, and soil moisture. The data was collected in the summers of 2017-2019, at the CLC. The remaining carbon data representing N and P are retrieved from various relevant literature with due acknowledgment provided at the appropriate places. The average monthly precipitation and temperature data are obtained from the Saskatchewan Research Council that reports weather summaries for the CLC (See Table 4.6).

Table 4.6 Average weather data at the conservation learning centre (2018)

Months	Average Temperature (^{O}C)	Precipitation (mm)
January	-16.10	20.10
February	-18.80	4.70
March	-9.80	25.70
April	-2.90	10.80
May	13.30	12.5
June	16.30	49.8
July	17.40	112.4
August	15.70	38.4
September	6.50	29.3
October	1.40	8.60
November	-8.70	26.50
December	-11.20	10.7

Note: Weather data from the Saskatchewan Research Council. The average precipitation includes both rainfall and snow.

The cost of production data and crop prices are extracted from the Saskatchewan crop planning guide (SCPG, 2019). The planning guide provides comprehensive estimates on production costs, ranging from inputs, depreciation, investment, utilities, and estimated yields for individual crops under varied soil zones. This annual publication provides average estimates of fertilizer recommendations and urges farmers to test their soils to identify their soil needs.

4.9 Summary of the methodology

To address how management decisions about land practices (e.g., crop rotation) impact soil carbon stocks, and to what extend the resulting carbon stocks influence the yield of various crops, two contiguous simulation approaches were adopted in this study. These two procedures are summarized in Figure 4.1. First, land management practices in terms of different annual crop rotation choices are modeled on a soil turnover model, RothC. The RothC model transforms the crop rotations selections, crop residue inputs (carbon remains from harvested crops stored in plant roots and stubble), and weather variables such as temperature, rainfall, and evaporation, soil carbon dynamics and stocks.

The weather variables strongly influence the decomposition of the plant residue into the resulting soil carbon and carbon dioxide emissions from the soil. The carbon stocks are then used as the precursors for the economic simulation where such carbon stocks are directly linked to crop yield through crop response functions. 3% of SOC's annual mineralization is implied from the standpoint of maximum decomposition of SOC to release plants' nutrients that directly impact crop yield. The released nutrients (N, P) from SOC are fed into the response functions to simulate crop yields, which are then translated into farm revenue using the projected average crop prices for 2019.

The insight into using the response functions for assessing the economic values of SOC stems from searching for established relationships between soil carbon and crop yield. Invariably, such a connection will allow the components of SOC to be transformed into monetary values through their impact on yield. The response functions provide such a secure pathway because they link mineralized N, P, and water directly to crop production.

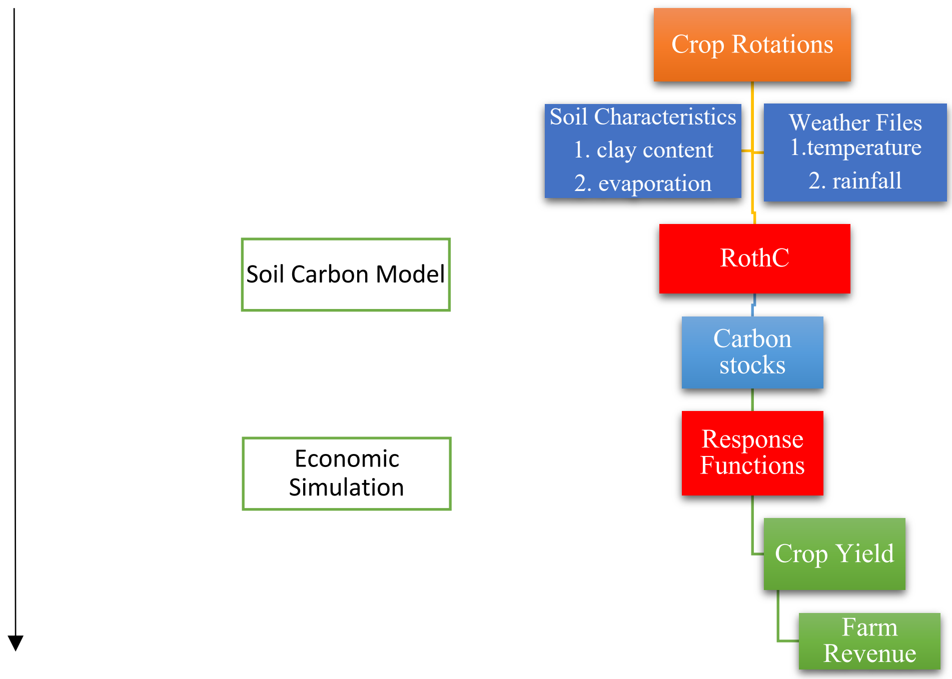


Figure 4.1 Hierarchical flow of the entire estimation

Therefore, an indicator of how the mineralized N, P, and water from the SOC source are measured became the next crucial parameter. Different techniques (or scenarios) were necessarily employed in this regard, giving that, SOC content of the soil is not constant but varies between soils. Thus, the estimation under each scenario is driven by how this research calculates mineralized N and P from SOC.

CHAPTER FIVE
RESULTS AND DISCUSSIONS

5.0 Introduction

This chapter presents the results of the study, highlighting the key insights, and discussing the potential implications therein. The first section of the chapter presents the results of the two separate and contiguous simulations estimating how management decisions, in terms of crop selection and rotation choices, influence the quantity of SOC stocks. The subsequent section then estimates the economic value of such carbon stocks. The results in each section are bound to both the simulation scenario and the complementary assumptions underlying the estimations.

5.1 Management practices and soil organic carbon stocks

This section introduces and discusses the simulation results from the RothC model. The soil carbon model was used to simulate SOC stock dynamics as influenced by crop rotation choices over time for a representative site with similar characteristics as the study area. As indicated in the methodology section, the crop rotations and crop selection choices are strongly inspired by the study area pattern of cultivated acreage of the crops involved. With wheat and canola being the major crops grown in Saskatchewan, barley was added into the rotation to allow for a dynamic crop rotation involving more than two crops. The simulation results are presented in scenarios where scenario 1 represents a 3-year wheat-canola-barley rotation produced over 20 years. In contrast, scenario 2 represents a 4-year canola-wheat-canola-barley rotation that features more frequent canola to reflect the more prominent canola production in the study area's landscape. For more discussion on the rotation schemes, refer to Table 4.2.

Like previous studies, the RothC model was run in reverse to calculate the plant carbon input to maintain the SOC stocks at the base year of simulation. The modeled (RothC) plant input is reported together with the carbon yield values in Table 5.1 for comparison. It appears RothC returns the same carbon input value for the three crops. This value of 1.23 t C ha^{-1} yr^{-1} is the amount of the annual carbon inputs that must return to the soil to maintain the carbon stocks in the base year of simulation. The uniformity of the value is credited to the same initial carbon stocks under which the three crops were subjected to in the first year of simulation. Intriguingly, there is no wide variation between the modeled values and the values calculated from yield (see Table 5.1) compared to similar values presented in Table 4.1 for earlier studies. In this study, the yield input values (in Table 5.1) were used for the actual simulation for two pragmatic reasons. One, to allow the results in this study to be comparable to previous studies that adopted an analogous approach. Second, and more importantly, the yield values represent the actual amount of crop residues that return to the soil after harvest in the study area, adjusted for yield outputs and forage production.

Table 5.1 Carbon inputs derived from RothC

Crop	RothC Values (t C ha^{-1} yr^{-1})	Yield (root + stubble)* (t C ha^{-1} yr^{-1})
Wheat	1.23	2.70
Canola	1.23	1.60
Barley	1.23	1.60

**yield values are reported previously in Table 4.1.*

The RothC simulations show both rotation schemes increasing the magnitude of the soil carbon stocks over time (see Figure 5.1 for trend). With the S-C-B rotation, an average annual addition of 1.63 t C ha^{-1} is estimated, whereas, that value stands at 1.55 t C ha^{-1} for the C-S-C-B rotation. What is evident with these estimates is that they approximately fall between the input-residue values started within the simulation (see yield values in Table 5.1). This buildup of SOC is generated because biomass (shoots and roots) that returns to the soil adds more to carbon stocks than the combined carbon depletion caused by grain removal and carbon emissions into the atmosphere through organic carbon decomposition (Petersen and Hoyle, 2016). Also, the rainfall level in the black soil zones favors minimal annual decomposition and subsequent leaching of nutrients, thereby allowing the resulting carbon to accumulate (Petersen and Hoyle, 2016). The rates of SOC increment, although reasonably small, are consistent with the average values reported in the literature. Plus, the regular rotations excluded N-rich leguminous crops such as soybeans and peas, which host N-fixing bacteria in their root zones, and the inclusion of any of those crops will most likely have increased the sequestrations rates presented in this study.

For the S-C-B rotation, the simulated additional carbon stocks rose from 9.38 t C ha^{-1} in 2017 to 15.24 t C ha^{-1} in 2037. However, for the S-C-B-C rotation, the additional carbon stocks grew from an initial level of 9.38 t C ha^{-1} in 2017 to 14.78 t C ha^{-1} in 2037. The increase in soil carbon stocks under the two different annual crop rotations are very similar and suggest the potential of the soil, under the specified management practices to store additional carbon with the resulting overall benefits to agricultural landscapes. This assertion corroborates the existing understanding that soil management in terms of conventional crop rotations is useful in conserving or increasing SOC stocks in the prairies (see Kimble et al., 1998, Belcher et al., 2003). Further, West and Post (2002) conjecture that crop rotations would take approximately 40 to 60 years to bring SOC back to its native grassland levels. In this study, it could be highlighted that soil carbon asymptotically approaches the maximum within the 20-year period under which the simulation was carried out as shown in Figure 5.1

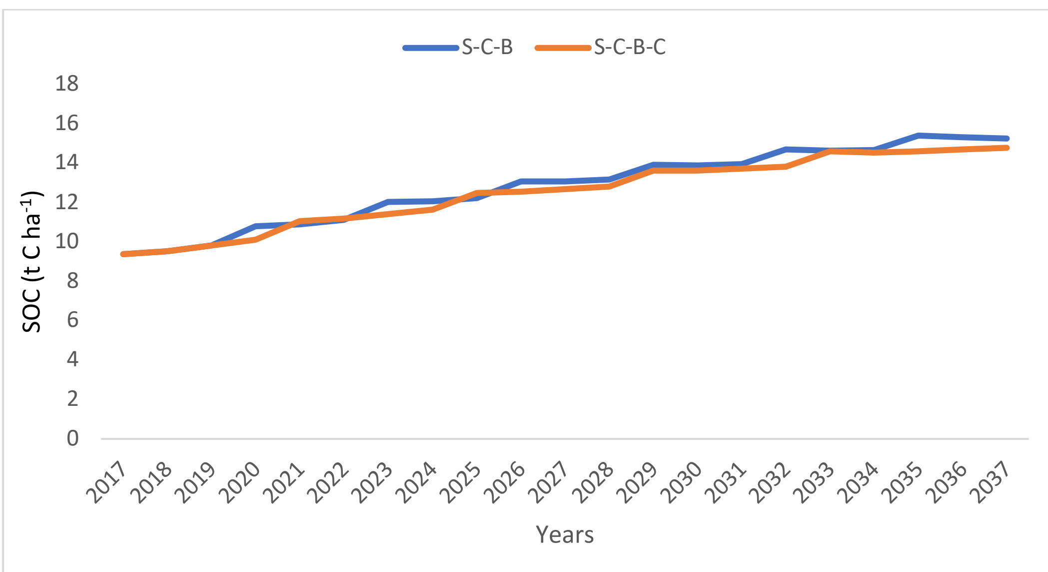


Figure 5.1 Carbon dynamics with canola, barley and wheat rotations from the RothC simulation

While larger soil carbon stocks represent a net potential benefit to farmers, Janzen (2006) notes that additional carbon stocks could quickly degrade and emit large volumes of carbon dioxide into the atmosphere when management practices change. Precisely, mineralization plays a crucial role in that development by ensuring that organic carbon breaks down to release the potentially available nutrients to plants. In the process, carbon dioxide is emitted into the atmosphere. Therefore, the corresponding levels of carbon dioxide emitted are reported in Table 5.2 for both rotations to understand how the rotation choices influence emissions as well. As shown in column 2 of Table 5.2, the carbon dioxide emissions increased over the entire duration, from 2017 to 2037, for both rotations. For instance, in the S-C-B, annual carbon dioxide emissions soared from 9.28 t C ha^{-1} to 41.92 t C ha^{-1} in 2037. This pattern is an indication that the two sequences are increasing carbon dioxide emissions from the soil. The relative emission power of the two rotations are shown in Figure 5.2.

In these estimates, as carbon stocks are increasing and accumulating in the soil, there is also a subsequent relatively higher level of carbon dioxide emissions into the atmosphere. I take the carbon dioxide released from an efficiency standpoint (higher carbon stocks emitting less CO_2) divide by the quantity of carbon stocks in a given year. The aim is to evaluate whether, under the same rotation practice, additional carbon stocks have a relatively higher or lower carbon dioxide emitting potential. The literature suggests that agricultural management practices sequester the lost carbon in the atmosphere and reduce the emission of the stocks already conserved. The last column of Table 5.2 describes how the current SOC levels influence the amount of carbon dioxide emitted. The results show that the two carbon dioxide emissions potential relative to the organic carbon stored. Over the entire simulation period, the emission coefficient fell from 0.15 in 2017 to 0.10 in 2037 under both scenarios.

Table 5.2 Ratio of carbon dioxide emissions to accumulated carbon stocks

	Cumulative CO_2 emissions (t C ha^{-1})		Changes in CO_2 Levels* (t C ha^{-1})		The ratio of CO_2 to SOC stocks	
Year	S-C-B	C-S-C-B	S-C-B	C-S-C-B	S-C-B	C-S-C-B
2017	9.28	9.27	-	-	-	-
2018	10.72	10.72	1.44	1.45	0.15	0.15
2019	12.04	12.04	1.32	1.32	0.13	0.13
2020	13.78	13.34	1.74	1.3	0.16	0.13
2021	15.25	15.08	1.47	1.74	0.13	0.16
2022	16.63	16.55	1.38	1.47	0.12	0.13
2023	18.44	17.94	1.81	1.39	0.15	0.12
2024	19.97	19.33	1.53	1.39	0.13	0.12
2025	21.42	21.16	1.45	1.83	0.12	0.15
2026	23.3	22.71	1.88	1.55	0.14	0.12
2027	24.9	24.18	1.6	1.47	0.12	0.12
2028	26.4	25.63	1.5	1.45	0.11	0.11
2029	28.33	27.52	1.93	1.89	0.14	0.14
2030	29.97	29.13	1.64	1.61	0.12	0.12
2031	31.5	30.64	1.53	1.51	0.11	0.11
2032	33.46	32.14	1.96	1.5	0.13	0.11
2033	35.13	34.06	1.67	1.92	0.11	0.13
2034	36.69	35.71	1.56	1.65	0.11	0.11
2035	38.66	37.25	1.97	1.54	0.13	0.11
2036	40.35	38.77	1.69	1.52	0.11	0.10
2037	41.92	40.28	1.57	1.51	0.10	0.10

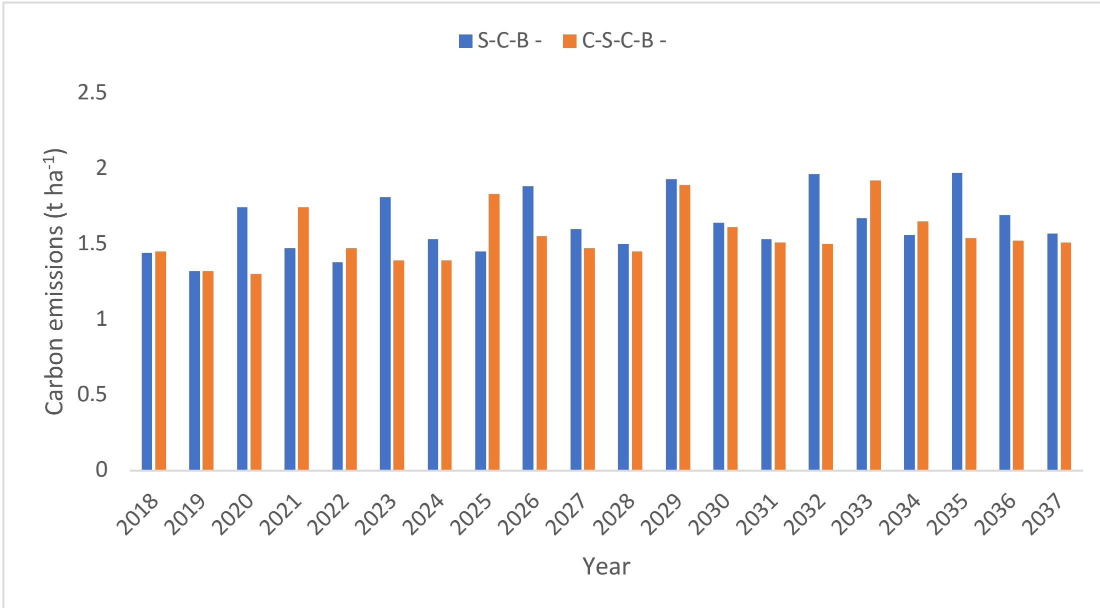


Figure 5.2 Relative carbon dioxide emissions between the two rotations

These coefficients are interpreted in this study to mean, the potential of the carbon stocks to emit carbon dioxide decreases from 0.15 to 0.10 over the period. Otherwise stated, the soil carbon stocks in 2017 emit 15% by weight of carbon dioxide than the stocks in 2037 that emit 10% of carbon dioxide. These simulations outcomes are the consequences of adopting management practices that result in conserving the SOC in agricultural farmlands. This overall reduction (from 0.15 to 0.10) is almost one-third of the initial emission rate started with under initial carbon stocks.

Based on the output from the RothC simulation modeling, maintaining the two rotations schemes over several years not only resulted in a buildup of carbon stocks but also portray a decreasing trend in the carbon dioxide emission rate. The overarching question is how much the carbon stocks benefit farmers directly after analyzing the impacts of the rotation choices on carbon stocks and carbon dioxide emissions. That whole discussion lays the foundation for the economic simulation and is discussed in the subsequent section.

5.2 The economic values of soil organic carbon

As outlined earlier, the economic value of SOC is linked to the ability of the stocks of soil carbon to provide mineralized N and P through mineralization and enhance soil water storage through aeration. The combined effect of mineralization and soil water conservation helps to improve plant growth and increase productivity. Using the response functions highlighted in Table 4.3 collectively with the results from the SOC simulations discussed in the previous section, the marginal contributions of such SOC are quantified in monetary terms through yield response. The study estimates the economic benefits of the carbon stocks in terms of the contribution to crop yield and farm-level revenue and decreases input cost due to less required purchased N and P. Following the estimation technique described in chapter four, this chapter presents the results of the estimations in this section under three scenarios with contemporaneous assumptions reiterated (at the beginning of each section) to provide a better context to understand the results.

In the first estimation, the mineralized N and P from the resulting carbon stocks (from the carbon simulation) are used as the basis for the estimation. The mineralized N and P are derived from the RothC-simulated-carbon and directly fed into the response functions to account for the value of SOC through its contributions to crop yield. This scenario will be termed as the RothC-output to give a descriptive name to the organic carbon (N and P) obtained from the RothC simulation. Meanwhile, the role of SOC in improving soil water storage is obtained by plugging the differences between the validation values of water needed for profit maximization and the annual precipitation rates in the study sites into the water response functions. In this analysis, I assume that the difference between the validation water balance and the average annual precipitation accounts for SOC's role in improving soil moisture conservation.

Average precipitation differs from the current rainfall patterns observed in the study site. In scenario 2 (known henceforth as a validation scenario), I digress from the carbon simulation results and use the validation nutrients of both N and P, together with a 10% adjusted increase in precipitation rate to gauge for the value of SOC. The name 'validation scenario,' therefore, signifies the use of the validation nutrients previously discussed in Table 4.4 under section 4.7.1 for the simulation. In the third scenario (hereafter called the field scenario), the field values replace the validation values of N and P (see Table 4.5), with a 10% adjusted decrease in precipitation rate to evaluate the value of SOC (see discussion under Tables 4.4, 4.5, 4.6 for the three crops throughout the discussion).

Finally, monetary values are reported in dollars per hectare to be consistent with the yield estimates from the response functions and to ease comparison with other studies. To better understand the results, the monetary values are interpreted as the dollar value of additional soil nutrients released through SOC mineralization. Also, central to this idea is the size of the SOC stock. With an assumed decomposition and mineralization rate of 3%, a lot more mineralized nutrients, such as N and P, will be available for plant growth with a SOC stock of 100 t C ha^{-1} than with a SOC stock of 10 t C ha^{-1}. Thus, relatively larger monetary values are associated with more extensive carbon stocks as well. Moreover, finally, the simulated monetary values should be interpreted to represent the maximum or upper bound, economic value potential for each scenario, given the limitations imposed by other factors such as pests and diseases, and the assumptions underlying the simulation itself.

5.2.1 Monetary values of SOC from the 'RothC-output.'

It must be reiterated that the monetrary and yield figures presented here do not symbolize yield-reductions that will be associated with having no SOC in the soil. Instead, the values represent decreased input costs due to the SOC providing N that will not need to be provided by purchased synthetic N fertilizer. In other words, farmers would have substituted the inorganic fertilizer should little/no N be released from SOC.

The mineralized N from the RothC output was translated into yield using the N response function; the corresponding revenue was between \$ CAD 1.71 t^{-1} C ha^{-1} and \$ CAD 17.14 t^{-1} C ha^{-1} for spring wheat (see Table 5.3). For emphasis and using the same technique for the other two crops, canola, and oats; the monetary values of the mineralized N were between \$ CAD 1.04 t^{-1} C ha^{-1} and \$ CAD 10.40 t^{-1} C ha^{-1} for canola and from \$ CAD 0.01 t^{-1} C ha^{-1} to \$ CAD 0.09 t^{-1} C ha^{-1} for oats. These estimates do not account for the possibility that plants may not capture some of the mineralized N due to potential N leaching (Wander and Nissen, 2004). It is essential to highlight that the lower and upper limits represent the minimum and maximum potential benefits associated with each of the nutrients under evaluation. The lower limit is estimated with 1% efficiency, while the upper threshold represents 10% efficiency (see methodology for further intuition). The economic values for spring wheat simulated over an entire duration of 20 years represent an annual sequestration benefit of \$ CAD 0.09 t^{-1} C ha^{-1} yr^{-1} to \$ CAD 0.87 t^{-1} C ha^{-1} yr^{-1} (similar sequestration values are put in brackets for subsequent analysis). For clarity, the sequestration benefits are interpreted to mean the marginal revenue contributions of increased carbon that is added into the soil organic carbon pool annually. These annual additions of soil carbon resulted from the combined effects of management practices and the sequestration potential of the soil. Under the carbon simulation results discussed earlier, an average value of 1.63 t^{-1} C ha^{-1} (see Table 5.2) of annual sequestration of organic carbon is obtained under the S-C-B rotation choice.

The revenue values presented above are equivalent to the value of the replacement-cost of inorganic fertilizer provided by mineralized N on the prairies. In terms of annual yield contribution, the upper monetary value of \$ CAD 17.14 t^{-1} C ha^{-1} of N for spring wheat is equivalent to yield values of 0.07 t ha^{-1} spring wheat.

Precisely, the additional yield value of 0.07 t of wheat is estimated from an equivalent amount of 2.19 kg of mineralized N (released from SOC mineralization). Explicitly, the 2.19 kg N is presumed to have come from approximately 70.00 t C stocks simulated from the RothC over the entire period of 20 years; however, if the resulting 2.19 kg of mineralized N released was quantified directly, with a unit price of \$ CAD 3.81 kg^{-1} a monetary value of \$ CAD 8.34 will have been obtained for the organic N.

Quantifying the monetary values of the mineralized N through the response function, therefore, provide in-depth values that go beyond input-replacement cost savings of having mineralized N. This is because organic N has a substantial impact on ensuring sustainable crop production. As was previously noted, where N availability is limiting crop production, increasing SOC can increase potential yield relative to other constraints by increasing the biological supply of nutrients from organic matter turnover (Petersen and Hoyle, 2016). This raises an enormous implication that productivity cannot be solely sustained exclusively through substitution of SOC loss with inorganic fertilizers (Aref and Wander 1997).

The SOC stock also has value for its contribution to soil P for plant growth. Incorporating the assumptions of the first scenario, the contributions of the mineralized P are approximate \$ CAD 2.20 t^{-1} C ha^{-1} (\$ CAD 0.03 t^{-1} C $ha^{-1}yr^{-1}$) on the lower limit and \$ CAD 21.97 t^{-1} C ha^{-1} (\$ CAD 1.10 t^{-1} C ha^{-1} yr^{-1}) on the upper limit for spring wheat. The corresponding values of mineralized P for canola and oats are \$ CAD 0.05 t^{-1} C ha^{-1} to \$ CAD 0.51 t^{-1} C ha^{-1} and, \$ CAD 0.21 t^{-1} C ha^{-1} to \$ CAD 2.51 t^{-1} C ha^{-1} respectively (see Table 5.3). The different monetary values between P and N stem from the differences in responses to N and P, rather than the amounts of the two nutrients used in the simulation. This is because the amount of the mineralized N and P that were released during the mineralization process in this scenario is subject to a constant mineralization rate (3%) and from equal carbon stocks. That is, the same amount of N and P are assumed under this simulation, but the differences in how the crops respond to the two nutrients explain the variation in their economic values.

Finally, soil water's importance represents a more uncertain economic value among the three crop production inputs simulated (see Table 5.3), except for canola. It appears the simulation returns a value of \$ CAD 1.41 mm^{-1} W ha^{-1} for spring wheat using water as the primary production input. The estimated monetary value of soil water under spring wheat, \$ CAD at 1.41 mm^{-1} W ha^{-1} is lower than that for canola (\$ CAD 12.52 mm^{-1} W ha^{-1}) and more than that for oats, \$ CAD 0.22 mm^{-1} W ha^{-1}. These figures, of course, significantly overlook soil water's role in maintaining other soil processes, such as enhancing microbial activities, aiding decomposition, and controlling soil temperature. These low economic values are partly accounted for by the lack of interaction between water and the other micro-nutrients in this modeling. Furthermore, even more critically, with rainfed agriculture, this model did not consider the cost of providing water to the prairies in the form of irrigation and thus did not factor in the price of water. The lower values are understandable, as farmers do not provide extra water to the crops in the study area, making the outcome in these estimates consistent with the crop management practices commonly used in this area.

Table 5.3 Economic values of SOC from the 'RothC-output'

Production input	Yield (t ha^{-1})	Revenue at 1% ($ CAD t^{-1} C ha^{-1})	Revenue at 10% ($ CAD t^{-1} C ha^{-1})
	Spring wheat		
Water *	0.01	1.41	1.41
N	0.69	1.71	17.14
P	0.89	2.20	21.97
	Canola		
Water *	0.03	12.52	12.52
N	0.24	1.04	10.40
P	0.01	0.05	0.51
	Oats		
Water*	0.00	0.22	0.22
N	0.01	0.01	0.09
P	0.22	0.25	2.51
Total (wheat)	1.58	5.32	40.52
Total (canola)	0.29	13.61	23.43
Total (oats)	0.23	0.48	2.82

**Water values are estimated at the same efficiency. 1% and 10% represent the percentage of marginal contributions of SOC to crop yield.*

Under ordinary soil growing conditions, the literature reports high variability in the availability of organic P relative to N (see Table 4.5 for reference). Subsequently, both N and P are decoupled in the next two simulations to adjust for the amount of each nutrient needed to maximize each crop profit rather than the amount resulting from the constant mineralization. Such discussions are elaborated further in the other two estimations.

The combined effects of the three crop production inputs (N, P, and W) provided by the simulated SOC stocks, which represents the value of SOC, yielded monetary value ranging from $ CAD 5.32 t^{-1} C ha^{-1} ($ CAD 0.27 t^{-1} C ha^{-1} yr^{-1}) to $ CAD 40.52 t^{-1} C ha^{-1} ($ CAD 2.03 t^{-1} C ha^{-1} yr^{-1}) for spring wheat as shown in Table 5.3**.** By using an econometric and environmental model, Belcher et al. (2003) estimated the economic value of SOC to be $ CAD 40.44 t^{-1} C ha^{-1} under organic rotations in the black soil zone with the same characteristics as the site used in this estimation. Therefore, the results are relatively consistent with comparable research. Under the RothC-output scenario, the total economic values of SOC for canola are lower with, an estimated value of \$ CAD 23 .43 t^{-1} C ha^{-1} (with 10% efficiency of SOC), declines to \$ CAD 2.82 t^{-1} C ha^{-1} with oats.

Two compelling explanations for the low economic values of SOC associated with oats are the low yield-response coupled with the low average prices of oats used in the simulation compared to the other crops. Overall, SOC increased the yields of spring wheat, canola, and oats by 1.58 t^{-1} C ha^{-1}, 0.29 t^{-1} C ha^{-1}, and 0.23 t^{-1} C ha^{-1}, respectively. At the time of the simulation, the projected prices of oats by the Saskatchewan crop planning guide was \$ CAD 3.10 per bushels relative to the \$ CAD 6.75 per bushels for spring wheat and \$ CAD 11.59 per bushels for canola. Thus, the lower economic values of the SOC to oats did not only mirror its declining contributions to yields but a true reflection of its monetary value through lower prices of the resulting crop output.

5.2.2 Monetary values of SOC under the 'validation scenario.'

The estimations using the validation values present a more sequential approach compared to the previous scenarios. The validation amount of N and P is used to estimate each crop yield in the first stage. For emphasis, these validation figures for N and P are the values that are required to produce crop yields that maximize their profits. In the second stage, a possible potential of 10% of the resulting yield in stage one is attributed to mineralized nutrients. For a justification of these corresponding percentages, see the methodology. Furthermore, SOC's role in soil water improvement is adjusted with a 10% increase in annual precipitation to mimic climate change situations where rainfall patterns increase. However, it should be interpreted with caution that an increase in precipitation only reflects a decreasing role of SOC in sustaining soil moisture for plant growth.

The added advantage of using the validation values in place of the RothC-output is that the validation values approach allows for the estimation of SOC's economic values at the profit-maximizing point for each crop. Besides, both organic and inorganic nutrients are allowed to interact so that an increase in the availability of inorganic nutrients will potentially scale down the role SOC plays to promote plants' growth. Using this estimation procedure, the marginal contributions of mineralized N in terms of crop revenue is between \$ CAD 1.38 t^{-1} C ha^{-1} (\$ CAD 0.07 t^{-1} C ha^{-1} yr^{-1}) and \$ CAD 13.79 t^{-1} C ha^{-1} (\$

CAD 0.69 t^{-1} C ha^{-1} yr^{-1}) for spring wheat (see Table 5.4). These estimated values are lower than for canola, which stands between $ CAD 1.95 t^{-1} C ha^{-1} and $ CAD 19.00 t^{-1} C ha^{-1}. However, the individual yield contributions of mineralized N to both spring wheat and canola are not reflected in these monetary estimations. From the viewpoint of yield values, the (mineralized) organic N improves yields of spring wheat by 0.56 t ha^{-1} and as much as 0.46 t ha^{-1} for canola. Nevertheless, because at the time of the analysis, the price of canola ($ CAD 11.59 per bushels) is much greater that of spring wheat ($ CAD 6.75 per bushels), the monetary values in canola tend to be higher than in wheat.

When the validation rates of P are used with the response functions for the simulations, the incremental yields associated with the three crops remained positive. Take spring wheat, for instance, the corresponding yield increment of 0.29 t ha^{-1} is equivalent to an economic value of $ CAD 7.23 t^{-1} C ha^{-1} ($ CAD 0.33 t^{-1} C ha^{-1} yr^{-1}) under the assumption of a 10% efficiency level for SOC. This value of $ CAD 7.23 t^{-1} C ha^{-1} for spring wheat represents a significantly lower revenue contribution relative to the value obtained under the RothC-output scenario ($ CAD 21.97 t^{-1} C ha^{-1}) for P. Nonetheless, the obvious inference that mineralized P reduces the demand for inorganic fertilizer to sustain crop yield is consistent.

As was previously remarked, the value of SOC is not tied down to mineralized N and P from mineralization, but its role in sustaining soil moisture for crop improvement. Therefore, SOC improves the yield of canola by 0.03 t ha^{-1}, through soil moisture enhancement, translated into an economic value of $ CAD 12.06 mm^{-1} W ha^{-1}. This economic value roughly represents 38% of the total monetary value of the CAD 31.61 t^{-1} C ha^{-1} that was obtained for SOC, placing it second to organic N with about 62% of the canola's economic value.

Table 5.4 Economic values of SOC under the 'validation scenario'

Production input	Yield (t ha^{-1})	Revenue at 1% (\$ CAD t^{-1} C ha^{-1})	Revenue at 10% (\$ CAD t^{-1} C ha^{-1})
Spring wheat			
Water *	0.01	1.56	1.56
N	0.56	1.38	13.79
P	0.29	0.72	7.23
Canola			
Water *	0.03	12.06	12.06
N	0.46	1.95	19.47
P	0.00	0.01	0.08
Oats			
Water *	0.002	0.24	0.24
N	0.00	0.00	0.00
P	0.01	0.02	0.06
Total (wheat)	0.85	3.66	22.58
Total (canola)	0.49	14.02	31.61
Total (oats)	0.01	0.24	0.30

**Water values are estimated at the same efficiency. 1% and 10% represent the percentage marginal contributions of SOC to crop yield*

The results for oats show a decreasing value even at the optimum. What should be noted is that the economic value of SOC (for oats) fell substantially using the validation scenario procedure to a \$ CAD 0.03 t^{-1} C ha^{-1}, of which 33% and 67% of the contributions emanated from water-enhancement and P respectively (see Table 5.4**)**. Recall this estimation was carried out for yield maximizing levels, where both organic and inorganic nutrients are allowed to interact. However, because inorganic nutrients are more soluble than the organic nutrients, the crops will perhaps utilize the already-available inorganic nutrients at their disposal, thereby decreasing the role of SOC in influencing yield. This could probably account for the low levels of revenue associated with using the validation values for the estimation.

The results in Table 5.4 suggests that SOC performs an aggregate function together with inorganic nutrients to improve the yield of crops considerably and subsequently reduce the variable cost of production. SOC increase the yields of spring wheat, canola, and oats, though through different magnitudes. For canola, this improvement in yield value is equivalent to $ CAD 31.61 t^{-1} C ha^{-1}, which is the cost of the equivalent inorganic fertilizer that will have to be supplied by farmers if SOC was not present in the soil. Of this value, N exerted the most significant influence of $ CAD, 19.47 t^{-1} C ha^{-1}. Where the average farmer holds hundreds of hectares of land, suggesting SOC has offset a significant proportion of their variable cost of production.

5.2.3 Monetary values of SOC under the 'field scenario.'

The estimates under the field scenario are not technically different from the previous two scenarios. The novel idea in these results is the change in assumptions made to capture another perspective of the same simulation. The fundamental assumption in this scenario is that farmers are urged by the SCPG to complement their soil fertility gaps with inorganic fertilizer that provide both N and P. If this is true, then, the initial amount of nutrients (N, P) in the soil was provided by soil carbon. Since measuring the exact amount of nutrients provided by the soil becomes cumbersome, requires accurate measurements, and will be expensive to monitor over time, this research estimate such value to lie between 1% and 10% of the field values (interpreted here as the efficiency of SOC).

Finally, the role of SOC in improving water efficiency is adjusted with a 10% decrease in the current precipitations levels to reflect changes in rainfall patterns. This decrease in rainfall is simulated to help understand that SOC becomes more useful in sustaining soil moisture and nutrients and that less mineralized organic nutrients will be lost through leaching. Again, the adjusted difference between the validation water and the current precipitation is used together with the response function to estimate the value of SOC under the water-enhancement effect. The results of the field scenario are presented in Table 5.5**.**

With this estimation procedure assuming that farmers apply the recommended fertilizers on their field, mineralized N improves the yield of spring wheat by 0.55 t ha^{-1} and canola by 1.04 t ha^{-1} (See Table 5.5). The economic value of N for spring wheat is approximate $ CAD 13.69 t^{-1} C ha^{-1} (upper limit), portraying a sequestration value of $

CAD 0.68 t^{-1} C ha^{-1} yr^{-1} over the entire 20-year duration of the simulation. This yield value of 1.04 t ha^{-1} is the maximum under the three scenarios created, possibly owing to the adjustment of the crop plant to the real field conditions. The relatively higher yield-improvement (1.04 t ha^{-1}) of N for canola is due to the abundance of SOC in the black soil zone. The mineralized N does not also get leached beyond the root-zone of the crops because of the proper water conservation practice adopted. Plus, water is less of a constraint to crop yields in the black soil zones, enabling crops to respond more positively to the benefits of increased SOC stocks (Belcher et al., 2003). The marginal economic values of SOC under the field scenario ranges from $ CAD 2.94 t^{-1} C ha^{-1} to $ CAD 17.90 t^{-1} C ha^{-1} (spring wheat), $ CAD 17.45 t^{-1} C ha^{-1} to $ CAD 57.72 t^{-1} C ha^{-1} (canola) and CAD 0.34 t^{-1} C ha^{-1} to $ CAD 0.64 t^{-1} C ha^{-1} (oats) and are fairly consistent with the simulations from the previous scenarios discussed earlier.

Table 5.5 Economic values of SOC using the 'field scenario'

Production input	Yield (t ha^{-1})	Revenue at 1% ($ CAD t^{-1} C ha^{-1})	Revenue at 10% ($ CAD t^{-1} C ha^{-1})
Spring wheat			
Water *	0.01	1.27	1.27
N	0.55	1.37	13.69
P	0.12	0.29	2.93
Canola			
Water *	0.03	12.98	12.98
N	1.04	4.43	44.33
P	0.01	0.04	0.42
Oats			
Water *	0.00	0.31	0.31
N	0.00	0.00	0.01
P	0.02	0.03	0.33
Total (wheat)	0.68	2.94	17.90
Total (canola)	1.08	17.45	57.72
Total (oats)	0.12	0.34	0.64

**Water values are estimated at the same efficiency. 1% and 10% represent the percentage marginal contributions of SOC to crop yield*

The economic values of water under the field scenario, to a great extent, show higher economic values as anticipated than the two previously simulated scenarios. These economic values range from \$ CAD 12.98 mm^{-1} W ha^{-1} for canola, \$ CAD 1.27 mm^{-1} W ha^{-1} for spring wheat to \$ CAD 0.31 mm^{-1} W ha^{-1} for oats (see Table 5.5). A possible explanation for this is that a 10% decrease in the precipitation, as assumed in this estimation, will make SOC's role in conserving water more crucial in maintaining crop performances. As soil water forms an essential component of plant biomass, its presence greatly influences other active processes in the crop-plant. Besides, the higher marginal economic values of water are not surprising as posited by economic understanding that the marginal utility benefits of an economic good increase with decreasing quantity. This finding, however, is contrary to results by Petersen and Hoyle (2016), who found that the value of SOC decreases with decreasing rainfall. They attribute their observation to high summer rainfall and temperatures experienced in zones with low growing-season rainfall, which causes soil organic N to be mineralized and subsequently leached before the growing season commences.

Generally, the results under the field scenario for canola, the field-based estimations show higher economic values of SOC compared to those from the RothC and the validation scenario. The principal reason explaining this outcome is that the field-based conditions reflect the realistic characterization of SOC roles in the prairies. Plus, conditioning the estimation to the field levels demonstrate the exact production scenario created in the estimation process. An added explanation for the disparity stemmed from the response functions themselves that were previously developed and then used to measure the response of crops in the black soil zones. The majority of these response functions took into consideration soils in Western Canada, which is the home to the black soil zones under the current study. Oats continue to contribute minimal economic values to SOC owing to the low response of the crop to each of the components of the SOC examined in this study, coupled with the low commodity prices available for the resulting yield. These results are consistent with the pattern of relatively small areas of agricultural land allocated to the production of oats in the black soil zones at large.

5.3 Cost of sequestering carbon

As previously noted, the variable cost of production for the three crops, spring wheat, canola, and oats as presented in Table 5.6, is estimated from the Saskatchewan crop planning guide (2019), which spells out the variable costs of production for individual crops across different soil zones. In this study, I capitalize on the average unit prices of N and P and then use such values to estimate the marginal cost of sequestering carbon. The rough estimates indicate the average unit price of N fertilizer is reported as \$ CAD 0.58 lb^{-1}, and P is \$ CAD 0.55 lb^{-1}. I further estimate that 1.6 t C ha^{-1}, which is the estimated average annual carbon additions or sequestered into the soil will yield approximately 105 lb of decomposed SOC to release N and P. If we quantify the decomposed component of the SOC at the average prices quoted above will result in \$ CAD 119 ha^{-1} marginal cost of sequestering carbon annually.

The estimated marginal cost value is contingent on the assumptions made above and the unit prices of the inorganic N and P referenced in the SCPG (2019). I assume a marginal cost value of \$ CAD 119.00 ha^{-1} is higher than the actual cost incurred by farmers because I quantified the non-usable component of the SOC inclusive. This disparity results because most of the SOC that is sequestered into the soil does not decompose to release mineralized nutrients for plant usage in the same year. Instead, such SOC mineralizes slowly and annually, and in some cases, does not provide direct inorganic nutrients to plants but supports soil function in different perspectives such as erosion control. Nevertheless, this estimating procedure is necessary because farmers will still have to sequester large quantities of SOC to benefit from the mineralized SOC for plant uptake.

Table 5.6 Estimated variable expenses on wheat, canola, and oats

Category	Variable costs	Wheat ($ CAD /acre)	Canola ($ CAD/acre)	Oats ($ CAD /acre)
Seed		24.41	66.19	29.57
Seed treatment		6.95	0.00	4.35
Fertilizer	N	62.53	64.27	57.32
	P	23.15	33.07	22.60
	Sulphur	0.00	7.73	0.00
Chemicals	Herbicides	44.56	49.99	23.70
	Insecticides	6.07	4.83	0.00
	Seed treatments	28.05	8.89	10.05
machinery operation	Fuel	24.34	23.13	25.21
	Repair	10.90	10.90	10.90
Hired labor*		19.75	17.75	17.75
Insurance premium		6.75	13.31	9.13
Utilities & miscellaneous		4.90	4.90	4.90
Interest on VC		6.87	7.98	5.64
Subtotal: fertilizer costs		85.68	105.07	79.92
Total variable cost		269.23	312.94	221.12
Nutrients costs as a % of VC		31.82%	33.58%	36.14%

(source: SCPG, 2019). *VC=variable cost.*

The estimated marginal cost value of \$ CAD 119.00 ha^{-1} is lower than the fertilizer cost forecasted by the crop planning guide. For each of the variable cost of fertilizer reported in Table 5.6 (see \$ CAD 85.68 acre^{-1} for spring wheat, \$ CAD 105.07 acre^{-1} for canola, and \$ CAD 79.92 acre^{-1} for oats), the equivalent cost per hectare is as follow; \$ CAD 211.63 ha^{-1} for spring wheat, \$ CAD 259.52 ha^{-1} for canola, and \$ CAD 197.40 ha^{-1}

for oats. With the approximate annual sequestration benefits of $ CAD 3.0 ha^{-1} of returns from investment in SOC sequestration, I conclude it will take about 40 years to realize the full gains from an investment in soil carbon sequestered in a one time period.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.0 Introduction

This final chapter provides the conclusions to the study, discusses the limitations, and highlights future research areas resulting from this thesis. The chapter also provides information and caveats regarding the interpretation of the result, their implication to the broader policy consideration, and how this thesis contributes to the overall NSERC Strategic Group research.

6.1 Summary, conclusions, and policy implications

In this study, management decisions in the form of crop selection and rotations are directly linked to the magnitude and monetary value of SOC's stocks. By using a carbon simulation model, RothC, the dynamics of such SOC stocks are analyzed together with carbon dioxide emissions. Two rotation simulation scenarios, involving three crops, form the basis for a representative crop rotation choice. With the fundamental assumption that the value of SOC is embodied in its ability to influence crop yield, crop response functions are used to measure the extent of such influence in the form of yields and then translated into revenue using the projected average crop prices. By first estimating the yield response of each crop to the various mineralized nutrients in SOC, the analysis further partitions the proportion of the total crop revenue that emanated from SOC sources. The estimating procedure also permits a variation in the proportion of total nutrients' sources from SOC.

The assumption of variable nutrients from SOC is crucial in the analysis since, under different climatic and geographical conditions, SOC contains different proportions of organic nutrients. Though the mineralization rate was maintained at 3% throughout the analysis, the study was still able to establish that nutrients from SOC could still differ based on the quality of the soil carbon itself (see Table 4.5).

The economic estimations were carried out for three crops; spring wheat, canola, and oats whose selections were profoundly shaped by their cultivated acreage in the black soil zone. To that extent, estimating the value of SOC through multiple crops allow the results to be compared and interpreted from different perspectives; crop type, and yields. The results of the RothC simulation, which show a marginal but sustained increase in SOC stocks, were consistent with the existing notion that crop rotations can build SOC stocks over time. The rate of increase of the SOC was found to be roughly proportional to the amount of biomass production in the production area. With annual carbon input additions from the various crops used in the simulation, the RothC model shows that most of the harvested remains of crop residue are incorporated into the soil as SOC.

The study also focuses on how the accumulation of SOC impacts the emissions of carbon dioxide. This analysis is a crucial element of contemporary studies that aim to establish an understanding of how land management decisions influence the carbon balance of agricultural soils. What appears as a revelation is that the amount of carbon dioxide emitted per unit of SOC stocks decreases as the amount of carbon stocks increases. The study found that, as SOC increased in the soil, less of the corresponding carbon dioxide is being emitted, suggesting that the stored carbon improved both soil function and subsequent sequestration.

Also, the combined finding that the two possible crop rotation choices adopted in this study have the potential to both increase the reserves of SOC, and cut down carbon dioxide emission can be generalized to explain the beneficial role even regular rotations play to ensure environmental quality. The decrease in carbon dioxide emissions associated with the rotations, though a serendipity finding, is vital amidst the calls for strategies to cut down greenhouse gas emissions coupled with the need to conserve soil organic carbon stocks. Irrespective of the motives for managing land resources, the ability to manage soils to maximize SOC contents by optimizing land use practices remains paramount (Wander and Nissen, 2004). An agricultural policy can thus promote adoption and to ensure sustainable activities in agriculture best management practices are in place. Policy instruments could play a role in promoting sustainable management practices in the agricultural sector with several key policy directions that can be deduced from the results of this study.

First, from a carbon pricing standpoint, a significant accomplishment has been achieved with the reduction of carbon emissions. This implies that a policy instrument that encourages and provides support (technically, R&D) to land managers for adopting soil management practices that contribute less carbon dioxide to greenhouse gas emissions can be put in place. With these coefficients specifying how much less the crop rotations are contributing emissions; the reductions coefficients can give a starting point about how much carbon farmers are sequestering from the atmosphere. With this knowledge of the sequestration rate combined with reductions in emissions, carbon pricing, which has become a new debate, can be factored into the decision-making process. However, the results show a private or internal monetary benefit to farmers who adopt management that sequesters more SOC. As a result, payment should not be necessary, but technical support or information may be appropriate. The sudy, however, did not insinuate that farmers will or should receive these supports for their enhanced carbon sequestration activities**.**

The results on the economic estimates of SOC appear consistent with previous studies that attempt to put an economic value on soil organic carbon, although this study adapts a different estimating technique. Ranging from studies done for the black soil zone (see Belcher et al., 2003) to those in different geographical regions such as in Western Australia (see Petersen and Hoyle, 2016), and even the United States (Wander and Nissen, 2004), the value of soil organic carbon appears positive under all crops and scenarios and did not deviate substantially from the previous findings.

What is noticeable and consistent from this simulation is that the value of SOC is driven by the crop yield- a key parameter underlying the estimations. In this study, SOC appears more valuable consistently under canola, followed by spring wheat and then oats in the three simulation scenarios adopted in the economic analysis. This hierarchical order of importance in terms of economic estimates fairly justifies the inclusion of canola as the valuable crop in the crop rotation choices utilized under the carbon simulation. The economic values differ slightly between crops and among scenarios, however, do not change the overall conclusion of the results substantially. The study finds that soil carbon influences crop yield most strongly through mineralized N, which plays a critical role in crop productivity.

The finding that decreasing precipitation patterns in the simulation results in additional increases in monetary values of SOC through soil-water effects paints a positive picture that SOC could become a buffer against changing climate conditions in the future. With this realization, building SOC could become a potential tool for mitigating the negative impacts of changing climate conditions through soil water conservation, controlling soil temperature, and increasing microbial activities.

Already, climate change models predict variations in rainfall patterns without precision, further creating doubts about the sustainability of existing crop yields. This is where the trade-off between future and existing profits comes to play in the agricultural landscape, where farmers will be willing to balance annual gains in farm revenue for sustainability in yields in the future. With SOC assumed to contribute between 1% and 10% of the total yield obtained from crops, the marginal value of SOC is recapped in this section. The estimations demonstrate a maximum economic value of SOC to be \$ CAD 57.72 t^{-1} C ha^{-1}, whereas a minimum value of \$ CAD 0.03 t^{-1} C ha^{-1}, depending on the crop type and the assumptions employed. This maximum value shows an annual sequestration benefit of \$ CAD 2.89 t^{-1} C ha^{-1} yr^{-1} over the entire 20-year duration of the estimation.

Wander and Nissen (2004) obtained a value of annual economic benefits of US\$ 3.15 t^{-1} C ha^{-1} for US agricultural soils, which are higher than the value obtained in this study. However, as with any economic good, the contributions of SOC to crop yield increase as more SOC is accumulated. The black soil zone under which this study is carried out contains original carbon content ranging from 60 t C ha^{-1} to 70 t C ha^{-1} compared to the 150 t C ha^{-1} started with by Wander and Nissen (2004) for the US agricultural soils. Thus, as SOC stocks increase, its contribution to yield as well as revenue increases as well.

The study estimates the annual marginal cost of sequestering carbon in the form of forgone fertilizer that will have to be supplied if farmers did not sequester such carbon. Comparing this cost value of \$ CAD 119.00 ha^{-1} to our sequestration revenue values between \$CAD 0.03 t^{-1} C ha^{-1} and C \$ CAD 57.72 t^{-1} C ha^{-1} yields strong evidence of the net benefits of building carbon stocks and, for that matter, the overall incentives to farmers for adopting management that sequester carbon. Nonetheless, as Petersen and Hoyle (2016) argue, not all farmers aim at maximizing profit or require high margins for practice change. Further, Lal (2014) reported that farmers price environmental goods subjectively and may adopt practices that sequester SOC accruing to the environmental or societal value they place on SOC.

Generally, the estimation procedure employed in this research adds novelty to understanding SOC's empirical values in the prairies. First, the estimations employed both field and experimental scenarios that enable the values of SOC to be examined from alternative perspectives. Second, the procedure represents the components of SOC into organic N, P, and the water enhancement elements that enable the discussion to be tailored towards the individual contributions of these SOC components. Lastly, the analysis attributes the value of SOC to its role in influencing crop output. This yield pragmatic results because the private benefits of SOC are the values inherently reflect the gains farmers obtain from conserving it.

With this research focusing exclusively on the on-site benefits, a lot more environmental and social benefits were conceivably overlooked. In countless situations, changes in management practices and land use generate numerous environmental gains, such as improved water quality, reduced soil erosion, provision of wildlife habitat, and visual amenities (Antle et al., 2001). If such supplementary benefits were incorporated into the analysis of soil carbon, the relative economic efficiency of alternative land use and management options could be different (Antle et al., 2001). Thus, these monetary values are underestimated, given the roles SOC plays, in addition to influencing crop yield, which is not directly measured by the response functions used for the evaluations. Nonetheless, future research that will compound both the on-site and off-farm benefits of SOC will be appealing to not only farmers but environmentalists and policymakers as well.
Finally, a simulation model that includes interaction terms for N, P, and water will probably yield economic estimates of SOC that will slightly paint a different picture of how SOC influences the yield of crops.

6.2 Research context

This research addresses part of the objectives under the broader NSERC Strategic Group. Under the auspices of linking soil quality indicators developed to crop yield, this study indeed translated the soil quality information gathered from the black soil zone to different crop yields. Information such as the amount of the SOC measured from the CLC is used as the initial carbon stocks for the carbon simulation to provide an understanding of the carbon dynamics overtimes. Also, information on organic N, P, and water from the site was used to form the basis of the economic simulations to estimate the economic value of the mineralized carbon. The overall fit of the thesis is its utilization of the comprehensive research data and its ability to answer the more significant project's precise research objectives, linking soil quality indicators to crop yield.

Again, the analysis and results in this thesis provide a more in-depth perspective on the carbon data collected from the conservation learning center. First, the carbon data was used for an economic analysis that allows for a broader understanding of the real data collected. Second, the results are used to provide a policy prescription that will guide both farmers and policymakers on their decisions regarding carbon sequestration and land management from an economic standpoint.

6.3 Contextual analysis and limitations of the study

It is crucial to indicate that the simulated carbon results in this thesis are based on the soil characteristics and function of the cultivated landscape of the Saskatchewan Conservation Learning Center. Other sites within the research center include the uncultivated grasslands where soil carbon data were collected as part of the NSERC Strategic research. However, to align the purpose of the study to the site, I analyzed the data for those landscapes where the land is annually cultivated, and annual crop rotations are produced.

Although the evaluation of the economic benefits of soil carbon sequestration can be broadened to include the effects of other GHG emissions, this study was restricted to only carbon dioxide and storage. This focus became central because the other gasses that form part of the GHG emissions do not present any direct benefits to farmers as private decision-makers. Therefore, the general implications of the research findings of using agriculture to mitigate climate change are constrained to only the carbon dioxide component of the total emissions in the sector.

Furthermore, the economic simulation's response functions did not allow the production inputs for crops to interact. Unlike conventional economic modeling, crop response functions are developed for individual crop production inputs such as N, P, and water. This is a critical assumption because crops absorb nutrients contingent on the availability of other nutrients in the soil. For instance, dry soil conditions can interfere with the amount of soluble organic N and P that crop plants can take. Thus, not allowing for nutrients interaction implies the economic impact of such production inputs on yield was estimated in isolation to the other conditions that might retard the utilization of such inputs in by crop plants.

Finally, there are competing soil carbon simulation models such as the Denitrification-Decomposition Model (DNDC) and CENTURY models that may provide more accurate predictors of SOC dynamics over time in the Saskatchewan Conservation Learning Center but was inappropriate for this study due to the complexity they present in their estimations.

6.4 Future research

Realizing non-input interaction could pose an ambiguity to the results presented in this study. The study recommends that further studies develop an empirical economic model that utilizes the response functions, yet allows them to interact in a way that is consistent with real-life production field conditions. This will inevitably enable the result to be construed from a field perspective.

The crop rotations used in this study also failed to capture leguminous and pulse crops due to the insufficient information on them for the RothC parameterization. Moreover, since legumes form an essential component of every crop rotation, including them on future studies will provide a deeper understanding of SOC dynamics at the CLC. I further recommend that future research on the impacts of SOC on crops yield be analyzed together with climate change models. This analysis will enhance the understanding of how SOC can mitigate the overall impacts of climate change variables such as temperature, precipitation, and humidity on annual crop yields.

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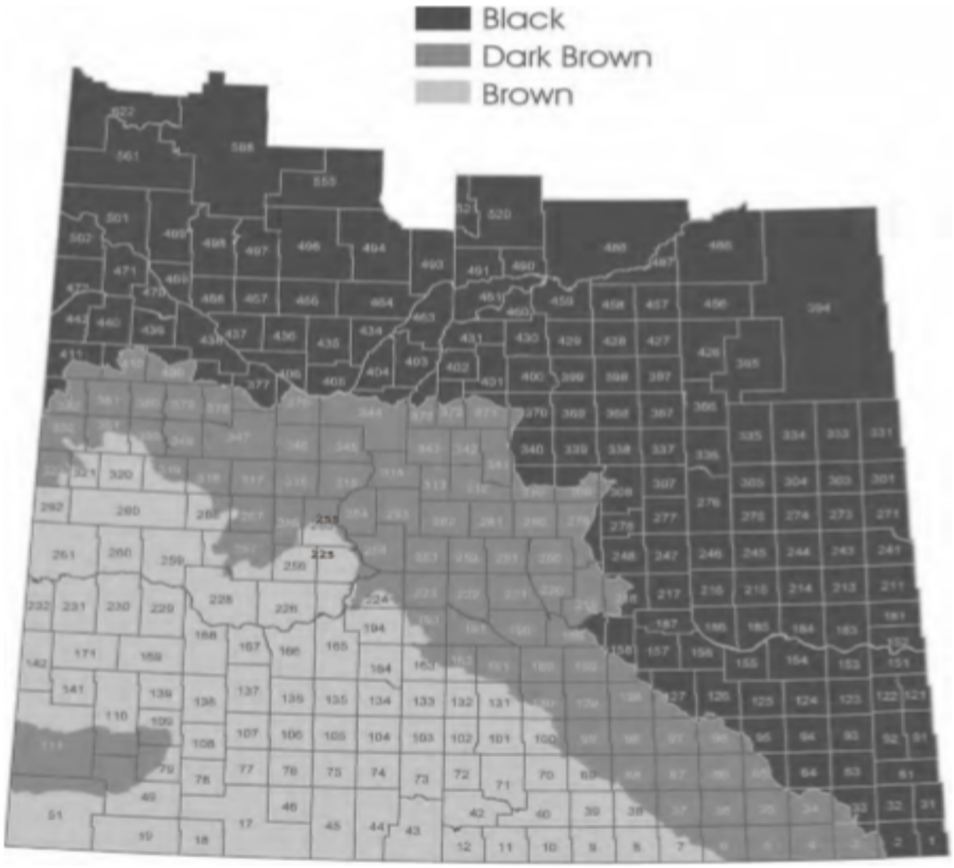
APPENDIX A



Relative land size of the black, dark brown and brown soil zones in Saskatchewan